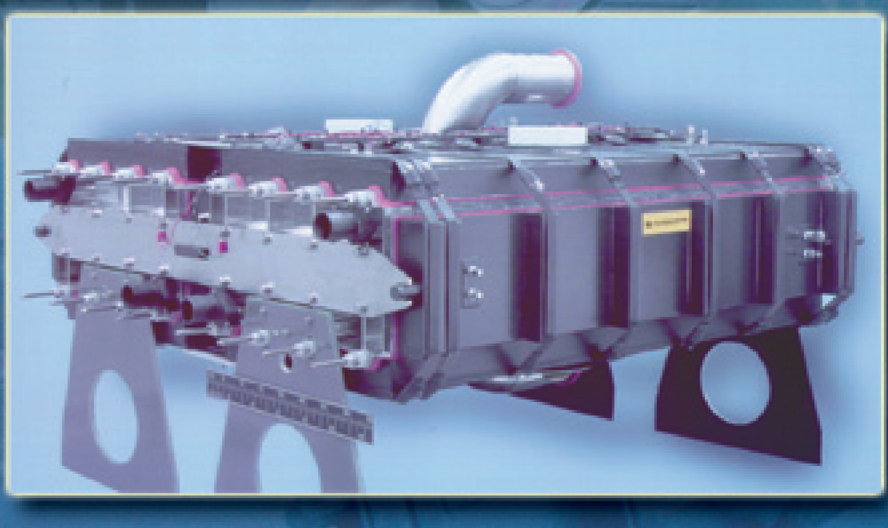
Lawrence Livermore National Laboratory

Sensor Needs and Requirements for
Proton-Exchange Membrane Fuel Cell Systems and Direct-Injection Engines



Sponsored by
U. S. Department of Energy
Energy Efficiency and Renewable Energy
Office of Transportation Technologies

UCRL-ID-137767

Sensor Needs and Requirements for Proton-Exchange Membrane Fuel Cell Systems and Direct-Injection Engines

Sponsored by
U. S. Department of Energy
Energy Efficiency and Renewable Energy

Office of Advanced Automotive Technologies

Edited by

Robert S. Glass
Lawrence Livermore National Laboratory

JoAnn Milliken, Ken Howden, Rogelio Sullivan
U.S. Department of Energy

May 2000

Cover Design by Frank Uhlig

Engine shown on the cover (top) is the Ford DIATA (Direct Injection, Aluminum, Through-Bolt Assembly) engine courtesy of Scott Low, Ford Motor Company

Fuel cell (bottom) is the International Fuel Cells, LLC PEM stack, gasoline reformer design, courtesy of Doug Wheeler, International Fuel Cells, LLC

Published by Lawrence Livermore National Laboratory
Applied Energy Technologies Program
P. O. Box 808
7000 East Avenue
Livermore, California 94551
Tel: (925) 423-2441
Fax: (925) 423-7914

Contents

Appendices

Acknowledgements

This workshop would not have been possible without the commitment of the eighty engineers and scientists who participated. The participants are listed in Appendix A. We also appreciate the companies, universities, and government agencies who committed the resources, both time and money, which allowed their employees to attend the workshop.

Special appreciation is extended to the invited speakers: Tom Cackette (California Air Resources Board), Doug Wheeler (International Fuel Cells, LLC), Rich Belaire (Ford Motor Company), and Joe Stetter (Illinois Institute of Technology). We also thank the panel members for the breakout sessions. For fuel cells, the panel members were: Doug Wheeler, Joe Stetter, Fernando Garzon (Los Alamos National Laboratory), and Jacob Wong (Ion Optics, Inc.). For the CIDI/SIDI engines breakout the panel members were: Rich Belaire, Richard Cernosek (Sandia National Laboratories), Joe Giachino (Visteon), Brage Golding (Michigan State University), and Paul Raptis (Argonne National Laboratory). In particular, we would like to acknowledge the point contacts on the panels, Fernando Garzon and Rich Belaire, who collected input from the other panel members and provided draft summaries from the breakout sessions. Putting the draft summaries together was greatly facilitated by the excellent notes taken by Fernando and Jeff Griffin (Pacific Northwest National Laboratory). Outstanding facilitation of the breakout sessions was provided by Tom Coleman and Pat Chance from Lawrence Livermore National Laboratory. They kept us focused and on track.

Finally, the workshop would not have been possible without the administrative assistance provided by Jane Rubert and Lisa Henson from LLNL. They did the bulk of the behind-the-scenes work that made the workshop run smoothly and efficiently.

Robert S. Glass
Lawrence Livermore National Laboratory

JoAnn Milliken, Ken Howden, Rogelio Sullivan
U.S. Department of Energy

Executive Summary

Workshop Objectives/Goals

On January 25 and 26, 2000, the Department of Energy (DOE) Office of Advanced Automotive Technologies (OAAT) sponsored a workshop on sensor needs for automotive fuel cell systems; compression-ignition, direct-injection (CIDI) engines; and spark-ignition, direct-injection (SIDI) engines. These technologies are being developed by OAAT under the Partnership for a New Generation of Vehicles (PNGV), a government-industry collaboration to develop vehicles having up to three times the fuel economy of today's mid-size automobiles.

The purpose of the workshop was to draw upon the expertise of the fuel cell development community, the DI engine community, and sensor researchers and manufacturers to define the needs and technical targets for sensors, and to aid DOE in identifying and prioritizing R&D activities in those areas. Sensors enhancing both proton-exchange membrane (PEM) fuel cell and CIDI/SIDI engine performance were of interest, as well as those for use in emission control, and for passenger safety. The objectives of the workshop were to:

- define the requirements for sensors
- establish R&D priorities
- identify the technical targets and technical barriers
- facilitate collaborations among participants

The recommendations from this workshop will be incorporated into the multi-year R&D plan of the DOE Office of Advanced Automotive Technologies.

Sensor Priorities and Requirements

Following the opening session, the workshop participants were divided into two working groups - one for fuel cells and one for CIDI/SIDI engines. Each group focused on the workshop goals identified above. For fuel cell systems, the high priorities are CO sensors which are needed to prevent fuel cell poisoning and hydrogen sensors for performance control and safety. For CIDI and SIDI engines, the highest priority is a NO_x sensor for emission control. For CIDI engines, sensors for control of particulate matter (PM) emissions are a high priority and wide-range oxygen sensors are a medium priority. A summary of sensor priorities and the technical requirements for each area are given below. Extended discussion for each sensor can be found later in this document.

SENSORS FOR AUTOMOTIVE PEM FUEL CELL SYSTEMS

Most commercially available sensor technologies have not been designed to operate in a fuel cell gas environment. The most common sensor design environment is ambient air, not fuel cell reformate gas streams. The major complaints are that the sensors that do work to varying degrees of success are too big and costly, and that sensors that are potentially low cost are not reliable or do not have the required lifetime. In some cases, neither performance nor cost targets can be met. Extensive research in redesign and development is needed for operation in a fuel cell gas environment. Careful testing of prototype devices in fuel cell stack/fuel processor environments will be needed to validate the performance of any sensor. Research, development, and validation should be carried out through careful coordination among industry, national laboratory, and university sensor researchers, sensor manufacturers, fuel cell system developers, and the automobile industry. Prioritized sensor needs for proton-exchange membrane fuel cell systems operating on direct-hydrogen and on reformed fuels are listed in Table 1.

Table 1. Requirements for PEM Fuel Cell System Sensors[a]

Sensor	Requirements
Carbon Monoxide	a) 1-100 ppm reformate pre-stack sensor – Operational temperature: <150 °C – Response time: 0.1 - 1 sec – Gas environment: high humidity reformer/partial oxidation gas- H_2 30-75%, CO_2, CO, N_2, H_2O at 1-3 atm total pressure – Accuracy: 1-10 % full scale b) 100-1000 ppm CO sensors – Operational temperature: 250 °C. – Response time: 0.1 - 1 sec – Gas environment: high humidity reformer/partial oxidation gas-H_2 30-75%, CO_2, CO, N_2, H_2O at 1-3 atm total pressure – Accuracy: 1-10 % full scale c) 0.1-2% CO sensor 250 °C -800 °C – Operational temperature: 250 °C –800 °C. – Response time: 0.1 - 1 sec – Gas environment: high humidity reformer/partial oxidation gas- H_2 30-75%, CO_2, CO, N_2, H_2O at 1-3 atm total pressure – Accuracy: 1-10 % full scale
Hydrogen in fuel processor product gas	– Measurement range: 1-100% – Operating temperature: 70- 150 °C – Response time: 0.1 -1 sec for 90% response of step function – Gas environment: 1-3 atm total pressure, 10-30 mol % water, total H_2 30-75%, CO_2, N_2 -- Accuracy: 1-10 % full scale
Hydrogen in ambient air (safety sensor)	-- Measurement range: 0.1-10% – Temperature range: –30 to 80 °C – Response time: under 1 sec – Accuracy: 5% – Gas environment: ambient air, 10 –98% RH range – Lifetime: 5 years – Selectivity from interference gases such as hydrocarbons is needed
Sulfur compounds (H_2S, SO_2, organic sulfur)	– Operating temperature: < 400 °C – Measurement range: 0.05 ppm -0.5 ppm – Response time: < 1 min at 0.05 ppm – Gas environment: Hydrogen, carbon monoxide, carbon dioxide, hydrocarbons, water vapor
Flow rate of product gas from fuel processor	– Flow rates: 30 -300 standard liters per minute – Temperature: 80 °C – Gas environment: high humidity reformer/partial oxidation gas: H_2 30-75%, CO_2, N_2, H_2O, CO at 1-3 atm total pressure
Ammonia	– Operating temperature: 70-150 °C – Measurement range: 1-10 ppm – Selectivity: <1 ppm from matrix gases – Lifetime: 5-10 years – Response time: seconds – Gas environment: high humidity reformer/partial oxidation gas-H_2 , 30-75%, CO_2, N_2, H_2O, CO at 1-3 atm total pressure
Temperature	– Operating range: -40- 150 °C – Response time: in the –40-100 °C range < O.5 sec with 1.5% accuracy; in the 100 – 150 °C range, a response time <1 sec with 2 % accuracy is sufficient

	– Gas environment: high humidity reformer/partial oxidation gas- H_2 30-75%, CO_2, N_2, H_2O, CO at 1-3 atm total pressure – Need to be insensitive to flow velocity
Relative humidity for cathode and anode gas streams	– Operating temperature: 30-110 °C – Relative humidity: 20-100 % – Accuracy: 1% – Gas environment: high humidity reformer/partial oxidation gas- H_2 30-75%, CO_2, N_2, H_2O, CO at 1-3 atm total pressure
Oxygen concentration in fuel processor and at cathode exit	(a) Oxygen sensors for fuel processor reactor control – Operating temperature: 200-800 °C – Measurement range: 0-20% O_2 – Response time: < 0.5 sec – Accuracy: 2% of full scale – Gas environment: high humidity reformer/partial oxidation gas- H_2 30-75%, CO_2, N_2, H_2O, CO at 1-3 atm total pressure b) Oxygen sensors at the cathode exit -- Measurement range: 0-50% O_2 – Operating temperature: 30-110 °C – Response time: < 0.5 sec – Accuracy: 1**%** of full scale – Gas environment: H_2 , CO_2, N_2, H_2O at 1-3 atm total pressure
Differential pressure in fuel cell stack	– Measurement range: 0-1 psig or (0-10 or 1-3 psig - depends on design of fuel cell system) – Temperature range: 30-100 °C; -40 °C survivability – Response time: <1 s – Accuracy: 1% – Size: Needs to be small - 1 square inch and orientation cannot be a problem – Other: has to be able to withstand and measure liquid and gas phases

[a] Sensors must conform to size, weight, lifetime, and cost constraints required for automotive applications

SENSORS FOR CIDI/SIDI ENGINES

Sensors for CIDI/SIDI engines are at a more mature stage of development than fuel cell sensors. While the sensors identified below currently exist for defined applications, there are no sensors available that fall into the highest need category and meet all of specifications required by the automotive industry. These specifications include operation in very harsh environments, high sensitivity and selectivity, long lifetime, low/no maintenance, high stability, and low cost. In addition, sensors need to be developed for specific systems, not generic operation, because manufacturers sometimes have different measurement strategies. Requirements for the high priority NO_x and particulate matter (PM) sensors, and for the medium priority wide-range oxygen sensor are listed in Table 2 .

Table 2. Requirements for CIDI/SIDI Sensors[a]

Sensor	Requirements
NO_x	– 20-300 ppm sensitivity for diesel (with potential for some applications up to 2000 ppm feed gas) – 100-200 ppm sensitivity for gas engines – Measurement precision within ± 5 ppm for diesel and within ± 20 ppm for gas engines – Temperature: 600-1000°C – Lifetime: 10 years; 150,000 miles for automobiles and 500,000 miles for trucks – Response time: 1 sec or less (must be 5 ms for cylinder-to-cylinder monitoring and 50-100 ms for engine control) – Separate measurements of NO and NO_2 – Immune to soot, sulfur and urea (NH_3)

	– Cost < $20.00
Particulate Sensor	— Smoke number under 2 BSU (Bosch smoke units) — Minimum detection: 0.2 BSU – Temperature: 600-1000 °C – Lifetime: 10 years; 150,000 miles for automobiles and 500,000 miles for trucks — Response time: 1 sec or less (must be 5 ms for cylinder-to-cylinder monitoring and 50-100 ms for engine control — Cost < $20.00
Wide Range O_2 Sensor	– Range is λ from 0.7-15 (includes diesel) – Response better than 4 Hz for engine control – Temperature range: ambient - 1000°C – Startup time less than 15 seconds – Resistant to poisoning from phosphorous, sulfur, lead and particulates – Cost ≤ $20.00

[a] Sensors must conform to size, weight and cost constraints required for automotive applications

May 2000

Robert S. Glass, Workshop Organizer, Lawrence Livermore National Laboratory

JoAnn Milliken, Program Manager, Transportation Fuel Cell Program, U. S. Department of Energy, Office of Advanced Automotive Technologies

Rogelio A. Sullivan, Program Manager, SIDI Engine Program, U. S. Department of Energy, Office of Advanced Automotive Technologies

Kenneth C. Howden, Program Manager, Light-Duty Diesel Engine Technology, U. S. Department of Energy, Office of Advanced Automotive Technologies

Introduction

To reduce U.S. dependence on imported oil, improve urban air quality, and decrease greenhouse gas emissions, the Department of Energy (DOE) is developing advanced vehicle technologies and fuels. Enabling technologies for fuel cell power systems and direct-injection engines are being developed by DOE through the Partnership for a New Generation of Vehicles (PNGV), a government-industry collaboration to produce vehicles having up to three times the fuel economy of conventional mid-size automobiles.

Sensors have been identified as a research and development need for both fuel cell and direct-injection systems, because current sensor technologies do not adequately meet requirements. Sensors are needed for emission control, for passenger safety and comfort, to increase system lifetime, and for system performance enhancement through feedback and control. These proceedings document the results of a workshop to define sensor requirements for proton exchange membrane (PEM) fuel cell systems and direct-injection engines for automotive applications. The recommendations from this workshop will be incorporated into the multi-year R&D plan of the DOE Office of Advanced Automotive Technologies.

The workshop attracted more than eighty participants. They included representatives from DOE, the national laboratories, automakers, the California Air Resources Board, universities, PEM fuel cell developers, fuel processor developers, CIDI/SIDI engine developers and manufacturers, and sensor manufacturers. The success of the workshop can be attributed to the diversity and sound technical foundation contributed by the participants. A complete list of the attendees is given in Appendix A.

The workshop consisted of invited talks and breakout sessions. A complete agenda is given in Appendix B. The plenary session included presentations from DOE program managers, and invited overview presentations covering present and future emissions regulations (Tom Cackette, CARB); the state-of-development of PEM fuel cells (Doug Wheeler, IFC); the state-of-development of CIDI engines (Rich Belaire, Ford); and the sensor field (Joe Stetter, IIT). Following the plenary session, two concurrent facilitated breakout sessions were organized - one focused on sensor needs for fuel cells and the other on sensor needs for CIDI and SIDI engines. For each session, a panel was formed to help guide the discussions. At the beginning of each session, the panel members gave brief opening comments. Members of the general audience were also invited to make short presentations. Summaries of the presentations are included in the report; visuals from the presentations are provided in Appendix C.

During the breakout sessions sensor needs were identified and prioritized, and performance criteria were defined. A large number of chemical and physical sensors were considered. Technologies not traditionally classified as sensors (e.g., infrared spectrometers or ion mobility mass spectrometers) were also discussed. It was recognized that revolutions/evolutions in optical and electronic technology could make these types of technologies available in the not-too-distant future. However, at this point in time, the sensor field can be considered to be more evolutionary than revolutionary.

Decades of development have gone into the development of electrochemical, spectroscopic, acoustic, and thermal sensors for chemical detection, and physical sensors. In large part, the challenge lies in the further development of specific materials, packaging, integration, and particularly in developing systems that are cost effective. In the final analysis, the best sensor approach for automotive applications should be selected based upon consideration of the analyte, required operational specifications, cost, and probability of success.

I. Summaries of the Plenary Session Presentations

"Overview of the DOE Transportation Fuel Cell Program," JoAnn Milliken, DOE

To reduce U.S dependence on foreign oil, the Department of Energy (DOE) Office of Transportation Technologies (OTT), in partnership with industry, is developing advanced vehicle technologies and fuels. Fuel cells, with their high efficiency, low-to-zero emissions, and fuel flexible characteristics, have emerged as one of the most promising technologies to meet the challenge. Fuel cell vehicles operating on gasoline, methanol, ethanol, or natural gas offer a pragmatic near-term option that can use the existing fuel infrastructure and accelerate fuel cell technology toward commercialization in vehicle applications. They will provide a transitional pathway toward a more sustainable long-term future based on renewable hydrogen as the requisite infrastructure is put into place. While the OTT Fuel Cell Program has made tremendous progress during the past 5 years, significant technical challenges remain. Through both industry and national laboratory R&D, OTT is addressing those challenges which include reducing the size, weight, and cost of the fuel processor and fuel cell stack subsystems, and developing automotive balance-of-plant components including air compressors, sensors, and controls.

" Overview of the DOE SIDI Engine Program," Rogelio Sullivan , DOE

Spark-ignited, direct-injection (SIDI) engines have been the focus of intense research at various times in the past, and have been at the doorstep of full production in the U.S. more than once. The principal attraction of SIDI engines is their potential high efficiency that stems from their stratified charge, lean-burn operation. In principle, SIDI should be able to utilize higher compression ratio and require little if any throttling for load control.

One of the primary barriers preventing the introduction of SIDI engines to the U.S. market has been emissions. The emission problem is being addressed through an integrated approach that considers the fuel, combustion control, and emissions treatment. In addition to emissions, the excessive cost of the high-pressure injection hardware is another important hindrance to commercialization of the technology in the U.S.

The DOE SIDI R&D program was initiated in FY 1999. The objectives of the program are to conduct research to enable SIDI engine introduction in the U.S., support technology development for emission control, and to provide a fallback option for CIDI. Because the DOE engine portfolio is heavily weighted with CIDI research, and the CIDI engine faces enormous emission and other potential drawbacks, it seems prudent to conduct enabling research on other high efficiency engine alternatives. The SIDI program is coordinated with the auto industry through the Low Emission Partnership (LEP) of USCAR. The program is reviewed and coordinated with the LEP on an ongoing basis.

The program's budget for FY 2000 is $6.9 Million and there are three major program thrusts:

- Fundamental Combustion Research and Modeling (national labs and universities)
- Engine and Component Research (contractors and national laboratories)
- Sensor Development (national laboratories)

Most of the ongoing sensor development projects in the SIDI program are conducted through a Cooperative Research and Development Agreement (CRADA) with the Low Emission Partnership. This work is primarily focused on the development of HC and CO sensors for on-board diagnostics and potentially engine control. This sensor CRADA has been in place since 1994 and involves Lawrence Livermore National Laboratory, Los Alamos National Laboratory, Argonne National Laboratory, and Sandia National Laboratories. The national laboratories have developed devices using a variety of novel sensing techniques, materials, and processing technologies. The automotive partners help to test and evaluate the sensors and provide guidance on technical targets and performance requirements. These CRADA projects will end in FY 2001.

This workshop will help to identify high priority sensor needs for SIDI engines. If a consensus can be reached on sensor needs during the breakout session and collaborative projects quickly formulated, then one or more new sensor projects may be added to the program this year. Potential projects will be screened for technology maturity, direct industry involvement, cost share, technical feasibility, and other program and policy factors.

"Overview of the DOE PNGV CIDI Combustion and Emission Control Program," Ken Howden, DOE

The Partnership for a New Generation of Vehicles, an industry-government consortium, has selected the compression-ignition, direct-injection (CIDI) engine as the basis for the development of hybrid electric mid-size passenger vehicles which will achieve up to 80 miles per gallon by 2004. The challenge in choosing this engine for the powertrain is to meet stringent Federal emissions standards while maintaining the high efficiency offered by the diesel cycle. The DOE contribution to this effort includes cooperative research with the automotive OEMs, suppliers, and the national laboratories in the areas of clean combustion and new emission control technologies. New R&D programs have also been established with U. S. diesel engine manufacturers to develop innovative emission control systems for CIDI passenger car engines. This technology will also be demonstrated on light trucks and sport utility vehicles for maximum impact across the light-duty fleet. Advanced petroleum-based fuels, a key element in optimized combustion and emission control system performance and durability, are also being developed in a parallel program with major energy companies and the automotive industry.

"Driving Towards Clean Air: Countdown to Zero," Tom Cackette, California Air Resources Board

Although Los Angeles remains one of the smoggiest cities in the nation, progress in reducing ozone has been substantial. The annual peak ozone has been reduced by 50% over the past 10 years to 0.17 ppm (the clean air goal is 0.09 ppm). Progress in reducing fine particles has been less, with unhealthy levels present on about 250 days per year.

The key to improving air quality is reducing hydrocarbon (HC), oxides of nitrogen (NO_x) and fine particle emissions (PM). Emission reductions of HC and NO_x well over 50% are needed to meet the ozone air quality standard. Mobile sources contribute about two thirds of these smog-forming emissions. Diesel engines are also a major contributor of directly emitted fine particles, which have been identified as a cancer causing substance, as well as a contributor to ambient PM.

Cars and light trucks have been the largest single source of smog-forming emissions. As car and light truck emissions are reduced in compliance with low emission vehicle standards, diesel engines, including those used in trucks, farm and construction equipment, and non-road vehicles such as locomotive and ships, become the largest source of smog-forming emissions (mainly NO_x), and also contribute about 70% of the public exposure to ambient air toxic compounds.

To achieve clean air in California, we need a substantial portion of vehicles to have zero or near zero emissions. This is most viable in the car and light truck, and urban heavy truck, sectors. Everywhere else, the application of best available technology is needed.

Near zero emission passenger cars (Nissan Sentra CA, Honda Accord EX) are being sold in California now, as are battery-powered electric vehicles and hybrid electric vehicles with very low emissions. Nearly every major auto manufacturer has promised introduction of fuel cell vehicles by mid-decade, and a unique industry/government partnership has been formed to address introduction of this new technology, including fuel and fueling infrastructure implications. Natural gas engines already emit less than one half the emissions of a heavy-duty diesel. However, diesel engine exhaust gas treatment devices that reduce NO_x and PM are becoming commercially available which create the likelihood for both diesel and natural gas engines achieving near zero emissions. Fuel cell engines also appear viable for use in heavy vehicles, especially those urban vehicles such as transit buses that could be fueled with hydrogen at a central site. Cost reduction remains the biggest challenge. Finally, automobile technologies such as the 3-way catalyst are being applied to industrial engines and boats. All these technologies benefit from the availability of low sulfur gasoline and diesel fuel.

In summary, the clean-up of all types of mobile sources, ranging from big ships to weed whips, is progressing rapidly. Zero and near-zero emissions are achievable for the major sources, including cars and diesel trucks. Clean fuels have enabled the use of clean-up technologies and pave the way for future innovations. Technology offers us a promising path to clean air.

<u>"State of Development of PEM fuel cells," Doug Wheeler, International Fuel Cells, LLC</u>

This presentation provided an overview of the three PEM fuel cell areas: Fuel Cells for Transportation Applications; Fuel Cells for Stationary Power Generation; and Fuel Cells for Portable Power Applications. PEM fuel cells for transportation offer the opportunity to replace the internal combustion engine (ICE) power source and to be used as auxiliary power units (APU). High efficiency and near zero emissions are two of the primary characteristics for both applications. The PEM-powered vehicle must also have a range comparable to the gasoline-fueled ICE and there is some indication that multiple fuel applications will become important.

Stationary power generation includes both residential applications and commercial applications. Power plants operating in the range 5 kW to 15 kW are suitable for the residential applications while the commercial applications will typically be in the range of 50 kW to 1 MW. High reliability, high efficiency, ultra-low emissions, and multi-fuel capability are primary characteristics for the PEM stationary applications.

PEM portable power plants are targeted for extended life with a rechargeable fuel and high power output. The power output would range from 5 watts to 1 kW while the fuel cells could be either mechanically or reversibly rechargeable.

Two major design concepts are being developed for PEM power plants: pressurized power plants operating at pressures as high as 4 bar and ambient pressure power plants operating near atmospheric pressure. The two concepts reflect two different methods for removing liquid water from the fuel cell. Pressurized fuel cells remove water through evaporation and entrainment of water droplets in the spent reactants. Pressurization is attained using a compressor/expander that requires a parasitic power of 10% to 20%. A high efficiency compressor/expander that can operate over the full range of power densities for the fuel cell has not been developed and is the subject of considerable research and development activities. On the other hand, ambient pressure power plants do not have this parasitic performance loss but require the development of bipolar plates that are porous and can wick the liquid water away from the fuel cell. The development of low cost porous bipolar plates is a focus of research for the ambient fuel cell power plants. Both the pressurized and ambient fuel cell power plants operate at 80 ^{o}C and the temperature limit appears to be a function of the membrane properties. The performance of the cells is very similar with the ambient fuel cell operating at 0.7 V @ 1000 mA/cm^2 on hydrogen and air with 90/60 utilization respectively. Full size automotive fuel cell stacks for both concepts, in the range of 40kW to 70kW, have been manufactured and tested in vehicles.

Fuel processing has been a major effort in the development of fuel cell power plants. Major components include the desulfurizer, fuel reformer, shift reactor, and preferential oxidizer. Desulfurization is a major technical hurdle with targeted sulfur levels of less than 0.05 ppm. Two types of reformer technology are being pursued: (1) autothermal reforming (ATR) and/or partial oxidation (POX) and (2) catalytic steam reforming (CSR). The choice of reforming technology is dependent on the application with ATR/POX addressing transportation needs of low volume and because of the ability to reform high carbon content fuels such as gasoline and diesel. The CSR technology is used with stationary where methane and propane are the fuels of choice and high efficiency is critical.

The shift reactor reacts water (steam) and carbon monoxide exiting the reformer to form hydrogen and carbon dioxide. To date, over 3 million commercial hours have been demonstrated in stationary commercial fuel cell applications using Cu/Zn catalyst. Improvements are necessary to reduce the volume of the shift reactor and these improvements may include the use of precious metal catalysts such as those under development at Argonne National Laboratory.

Preferential oxidation, also called selective oxidation, reduces the remaining carbon monoxide in the fuel processor gas stream to levels compatible with the fuel cell, e.g., 10 ppm. Ammonia is formed in the ATR/POX and is not removed by preferential oxidation. An additional scrubbing system maybe needed to remove the ammonia.

PEM power plants approach the performance levels required for transportation, stationary, and portable applications. Key component issues for the PEM power plant to be resolved are cost, power density, and durability.

“Overview of the State-of-the-Art in CIDI Engine Technology,” Rich Belaire, Ford Motor Company

A comparison was made between technologies of current CIDI engines in widespread use today and emerging designs. Primary distinguishing features are the move toward high-pressure, common rail fuel injection systems, variable geometry turbocharging, 4-valve per cylinder architecture and sophisticated exhaust aftertreatment devices concentrating on control of NO_x and particulate matter.

Analytical tools are being applied to guide the design of DI combustion systems with a view towards reducing engine-out emissions and improving NVH (noise, vibration, and harshness) while maintaining the fuel economy advantage of diesel engines. Examples of some of the latest European production engines were given.

“Sensors Overview,” Joseph Stetter, Illinois Institute of Technology

The world of chemical sensors is highly diverse and spans disciplines from physics and materials science to analytical chemistry and biology. Modern sensors are built on many platforms producing optical, electrochemical, mechanical, and thermal signals that correlate with the chemical variable of interest. A complementary approach is the miniaturization of large instruments like mass spectrometers, IR spectrometers, and chromatographs. While these are not strictly chemical sensors, the end result can be the desired one, i.e. high performance, low cost, rugged, stable, and long life measurements of the chemical variable needed for automotive process control, safety and environmental monitoring. The automotive requirements for gas measurement of CO, O_2, HCs, H_2S, NH_3, NO_x, PM, SO_2 and the like in a small, robust, and low cost package that can withstand the severe automotive environments is a tall order for existing sensors. However, chemical sensor technology is in all stages of development from laboratory curiosity to already performing some field applications. It is the latter that we need to develop and modify to meet the near-term needs of emerging automotive technologies making them more environmentally acceptable, with higher performance, and customer safe.

The proposed sensor program is extremely important to the success of the DOE mission and to the country. It is clear that more sensor activity occurs abroad in terms of conferences, programs, and in many fields sensors are imported. The DOE program strengthens the U. S. infrastructure in chemical sensor development and will result in new developments that are enabling to the new advanced automotive technologies. Guidelines for preparation of proposals as well as the evaluation of the work need to be developed based around sound chemical sensor science and the principles of analytical chemistry. The current workshop will go a long way toward defining the appropriate goals for our sensors. Future workshops can focus on initial results and on equitable formulas for evaluation and benchmarking our progress on the important technology developments in chemical sensors for advanced automotive applications.

II. Fuel Cell Sensors

A. Breakout Session – Presentation Summaries

Doug Wheeler (International Fuel Cells, LLC):
Diagnostic sensors are at an early stage of development for PEM fuel cells; a large number of sensors are needed.

Sensors currently used:

- thermocouples for the stack- 70-90 °C; reformer; low temperature shift reactor; POX reactor; heat exchangers. Thermocouples are probably adequate
- pressure
- differential pressure
- mass flow
- liquid level
- temperature switches
- level switches
- flow switches
- O_2/air utilization (0-20%)-now using a high temperature oxygen sensor
- water conductivity, fluoride ion also used for diagnostics

Sensors that need development:

- hydrogen sensors

– CO sensors (0-500 ppm)

Fernando Garzon (Los Alamos National Laboratory):

– reconfigured electrode structures are more CO tolerant by an order of magnitude with respect to previous designs
– sensor for measurement of CO in H_2 still needed
– reliable H_2 sensor needed
– reliable mass flow sensors are also needed

Shuh-Haw Sheen (Argonne National Laboratory):

– For a hydrogen sensor, acoustic sensor using sound velocity and attenuation is potential method-hydrogen has a very high sound velocity in comparison to other gases. However, cost needs to be lowered for market acceptability.

Jacob Wong (Ion Optics, Inc.):

– Non-Dispersive Infrared (NDIR) gas sensor technology should not be misconstrued to be the same technology as IR spectrometers used in a laboratory setting. The latter are expensive, fragile, and bulky instruments that make very precise gas concentration measurements. NDIR gas sensors are an evolutionary product of IR gas sensors that have emerged over the last decade. NDIR sensors are small, rugged, sensitive, and inexpensive and have performance which in some cases is better than their "IR spectroscopic" counterparts
– NDIR is a viable technology that should not be overlooked. Detection limits for CO are good; and it may also be possible to simultaneously measure other gases present such as CO_2, H_2O, HCs, NH_3, etc.

B. Sensor needs, priorities, and technical requirements

Following the introductory comments by the panel and audience, the breakout session endeavored to answer the following questions:

- What do we want the sensors to measure/detect?
- What are the technical and performance targets?
- Are currently available sensors adequate/appropriate?

  (a) If they are not, how can they be modified or improved?

  (b) If none are available, how do we develop new sensors?

- What are the barriers to development of new sensors?
- What organizations are best suited to develop new sensors?

In general, it was the consensus that most commercially available sensor technologies have not been designed to operate in a fuel cell gas environment. The major complaints are that the sensors/instruments that do work, to varying degrees of success, are too big and costly and the sensors that are potentially low cost are not reliable or do not have the required lifetime. In some cases, neither combination of specifications can be met. The most common sensor design environment is ambient air, not fuel cell reformate gas streams. Extensive research in redesign and development are needed for operation in a fuel cell anode gas environment. Careful testing of prototype devices in fuel cell /fuel processor environments will be needed to validate the performance of any sensor. The research, development, and validation should be carried out by careful coordination between industry, national laboratory, and university sensor researchers, the device manufacturers, fuel cell component manufacturers, and the automotive industry.

Sensor needs were determined by polling the audience. The sensor needs were then prioritized by voting on the initial list of 26, some of which were combined. After the top priorities were identified, the breakout session participants divided into smaller groups to discuss the specific sensor requirements. These were then presented to the entire group for further discussion/clarification. The results are listed according to the number of votes received in descending priority, along with the identified requirements.

Priority 1: CO sensors for various concentration ranges and environments

CO sensors were considered the most vital sensor need for PEM fuel cell operation because of anode poisoning that occurs when concentrations of 5-100 ppm of CO are present in the fuel gas stream. Based upon input from fuel cell developers, CO sensors for three different operational regimes were identified. The sensors and their requirements are:

a) 1-100 ppm reformate pre-stack sensor

- Operational temperature: <150 ^{o}C
- Response time: 0.1 - 1 sec
- Gas environment: high humidity reformer/partial oxidation gas- H_2 30-75%, CO_2, CO, N_2, H_2O at 1-3 atm total pressure

  For reformed gasoline the composition is:

Component	Before SOX (PROX)	After SOX (PROX)
H_2	34.8	32.1
H_2O	28.6	29.1
CH_4	0.4	0.4
CO	0.7	<10 ppm
CO_2	14.8	14.9
N_2	20.4	23.2
Ag	0.3	0.3

– Accuracy: 1-10 % full scale

b) <u>100-1000 ppm CO sensors</u>

– Operational temperature: 250 ^oC.
– Response time: 0.1 - 1 sec
– Gas environment: high humidity reformer/partial oxidation gas-H_2 30-75%, CO_2, CO, N_2, H_2O at 1-3 atm total pressure
– Accuracy: 1-10 % full scale

c) <u>0.1-2% CO sensor 250 ^oC -800 ^oC</u>

– Operational temperature: 250 ^oC –800 ^oC.
– Response time: 0.1 - 1 sec
– Gas environment: high humidity reformer/partial oxidation gas- H_2 30-75%, CO_2, CO, N_2, H_2O at 1-3 atm total pressure
– Accuracy: 1-10 % full scale

The following technologies were identified as being commercially available:
metal oxide semiconductor resistive sensors, IR spectroscopic devices, low temperature electrochemical sensors (not based upon the ion-conducting ceramic oxides used for current automotive applications), and colorimetric – dye based devices. All of these devices have limitations as identified in Table 3 below. Potential solutions that could be employed to make the current sensors useful for the CO sensing applications are provided.

Table 3. Available Sensors and Their Limitations for PEM Fuel Cell Applications

	MOS sensors	IR spectroscopic	Electrochemical	Colorimetric
Problems	Do not work in reducing environments; humidity interference, cross sensitivity	First generation technology was expensive, had limited lifetime, and window fouling.	Designed for air monitoring; operating temperature and lifetime limitations	Poor accuracy; temperature and lifetime limitations
Solutions	Need new semiconductor materials	Claims that new NDIR technology is now available and should be tested. Down the road, third generation technology - lower cost "spectrometers on a chip" may become available	Redesign for fuel gas environment; need high temperature electrolytes	Need new CO-sensitive dyes

This table does not imply that simple solutions for current technologies are available to make them useful for CO sensors. The entire list of specifications must be met and we have only highlighted important but partial solutions. There are a number of technical barriers that prevent current sensors or instruments from meeting the needs, and citing all of these and the potential solutions is beyond the scope of this document. Indeed, there is not universal agreement on all the required specifications among the engineers from different companies who design fuel cell systems. Collaborative R&D programs including sensor designers (industry, national laboratories, universities) and end users were identified as ways to develop new CO sensors; currently available technologies probably cannot be simply modified to meet performance and cost needs. The major non-technical barriers to development are research costs and market size, which translates into risk for business.

Priority 2: Hydrogen sensors for product gas

A hydrogen sensor for fuel gas quality measurement was also identified as a very high priority. The operating conditions are as follows:

- Measurement range: 1-100 % hydrogen concentration
- Operating temperature: 70- 150 °C
- Response time: 0.1 -1 sec for 90% response
- Gas environment: 1-3 atm total pressure, 10-30 mol % water, total H_2 30-75%, CO_2, N_2 (see table above for CO sensors)
- Accuracy: 1-10 % full scale

Numerous hydrogen-sensing technologies are available including thermal conductance, MOS semiconductor sensors, electrochemical sensors, palladium thin film resistance sensors, and acoustic sensors. Operating temperature, cross sensitivity, and cost are the major barriers to implementation. Validation in fuel cell environments is expensive and strongly needed. Sensor manufacturers, national labs, universities, and fuel cell manufacturers may conduct research.

Priority 3: 1% hydrogen in ambient air, safety sensor

A hydrogen sensor that operates in the 0.1 to 10 % hydrogen concentration range was also identified as a major need because of the potentially explosive nature of hydrogen/ air mixtures. This sensor would operate in the ambient environment, i.e., inside the passenger compartment of the fuel cell-powered vehicle.

- Temperature range: –30 to 80 °C
- Response time: under 1 sec
- Accuracy: 5%
- Gas environment: ambient air, 10 –98% RH range
- Lifetime: 5 years
- Selectivity from interference gases such as hydrocarbons is needed

Many sensor technologies were identified. The two most common commercially available technologies are MOS sensors and electrochemical sensors. These sensors need to be validated for cross sensitivity, lifetime and accuracy. Existing suppliers working closely with the fuel cell manufacturers and the transportation industry might develop the ambient air hydrogen gas safety sensor.

Priority 4: Sensors for sulfur-containing molecules

Very low levels of sulfur (from H_2S, SO_2 and organic sulfur) can adversely affect the performance of PEM fuel cells. Sensor requirements are:

- Operating temperature: < 400 ^oC
- Measurement range: 0.05 ppm -0.5 ppm
- Response time: < 1 min at 0.05 ppm
- Gas environment: see table above for CO sensors

It was the consensus from the fuel cell manufacturers that this sensor is needed upstream from the ATR/POX and fuel cell. Therefore, the sensor would be used as a sulfur detector in the fuel line. Alternatively, the detector could be at the exit of the desulfurizer or entrance to the ATR/POX where it would be a gas phase detection unit.

Existing technologies consists of electrochemical hydrogen sulfide sensors and spectrometric methods. Current technology is not designed to operate in the fuel cell environment.

Elimination of sulfur in the liquid fuel supplied would reduce the need for this sensor. Sensor manufacturers, national labs, universities, and fuel cell manufacturers might conduct research.

Priority 5: Flow rate sensors - product gas

Knowledge of the flow rate of the product gas from the fuel processor is needed for system feedback control. Operational requirements are as follows:

- Flow rates: 30 -300 standard liters per minute
- Temperature: 80 ^oC. (This is valid at exit of fuel processor; a flow sensor in the fuel processor is not recommended)
- Gas environment: high humidity reformer/partial oxidation gas: H_2 30-75%, CO_2, N_2, H_2O, CO at 1-3 atm total pressure

The following existing technologies were identified: differential pressure sensors; thermal mass hot wire; magnetic sensing; and acoustic methods. All methods face problems with variable gas composition, two-phase gas/liquid flow, and condensation at high humidity. Without initiating new sensor development efforts, current sensor manufacturers working together with the fuel cell manufacturers may be able to adapt existing technology. One barrier to development is market demand.

Priority 6: Ammonia gas sensor

Ammonia is an unwanted chemical byproduct originating from reaction of nitrogen in injected air streams with hydrogen gas. It inhibits fuel cell performance and measurement is desirable from a fuel cell performance standpoint. Sensing requirements are as follows:

- Operating temperature: 70-150 ^{o}C
- Measurement range: 1-10 ppm
- Selectivity: < 1 ppm from matrix gases (see table for CO sensors)
- Lifetime: 5-10 years
- Response time: seconds
- Gas environment: high humidity reformer/partial oxidation gas- H_2 30-75%, CO_2, N_2, H_2O, CO at 1-3 atm total pressure

Available sensor technologies include MOS sensors, electrochemical sensors, IR spectroscopic, chemiresistive devices, and surface acoustic wave devices. The currently available technology is either not designed to operate in a fuel gas environment or is prohibitively expensive. Partnerships with fuel processor developers and sensor developers (industry, national labs, and universities) are necessary to develop sensors meeting necessary requirements.

Priority 7: Temperature sensors

Fast responding temperature sensors are needed throughout the fuel processor and the fuel cell stack.

- Operating range: -40-150 ^{o}C
- Response time: in the -40-100 ^{o}C range < 0.5 sec with 1.5% accuracy; in the 100 – 150 ^{o}C range, a response time <1 sec with 2% accuracy is sufficient
- Gas environment: high humidity reformer/partial oxidation gas- H_2 30-75%, CO_2, N_2, H_2O, CO at 1-3 atm total pressure
- Must be insensitive to flow velocity

Existing technology includes thermocouples, RTD’s, thermistors and IR sensors. The major problem with these current technologies is response time and cost. Temperature sensor manufacturers can collaborate with fuel cell manufacturers to customize their products for the specific needs.

Priority 8: Relative humidity sensors

- Fuel cell membranes need constant humidification for proper operation. A humidity sensor may be needed for both cathode and anode gas streams.
- Operating temperature: 30-110 ^{o}C
- Relative humidity: 20-100 %
- Accuracy: 1%
- Gas environment: high humidity reformer/partial oxidation gas- H_2 30-75%, CO_2, N_2, H_2O, CO at 1-3 atm total pressure

Current technology includes thin film capacitance sensors, resistive sensors, and dew point systems. Problems with existing technology include operating temperature (limits at 60-65 ^{o}C) and response time, and high relative humidity measurements are problematic. Partnerships with fuel processor developers and sensor manufacturers may help to develop these devices.

Priority 9: Oxygen concentration sensors

(1) Oxygen sensors are needed for fuel processor reactor control purposes.

- Operating temperature: 200-800 ^{o}C
- Measurement range: 0-20% O_2
- Response time: < 0.5 sec
- Accuracy: 2% of full scale
- Gas environment: high humidity reformer/partial oxidation gas- H_2 30-75%, CO_2, N_2, H_2O, CO at 1-3 atm total pressure

(2) Oxygen sensors are also needed at the cathode exit

- Measurement range: 0-50% O_2
- Operating temperature: 30-110 ^{o}C
- Response time: < 0.5 sec
- Accuracy: 1% of full scale
- Gas environment: H_2 , CO_2, N_2, H_2O at 1-3 atm total pressure

High temperature electrochemical oxygen sensors are available from automotive suppliers. However, these types of sensors need to be validated in fuel cell gas operating environments. Low temperature electrochemical oxygen sensors are also available. These also need to be validated in cathode-exit gas environments. Oxygen sensor manufacturers can collaborate with fuel cell manufacturers to customize their products for specific needs.

Priority 10: Differential pressure sensors

Accurate, sensitive differential pressure sensors are desirable for use in the fuel cell stack for aiding in water management. These sensors need to have accuracy in inches of water.

- Measurement range: 0-1 psig and 0-10 psig (low range for atmospheric fuel cells and high range for pressurized fuel cells)
- Temperature range: 30-100 ^{o}C; -40 ^{o}C survivability
- Response time: <1 s
- Accuracy: 1%
- Size: Needs to be small - 1 square inch and orientation cannot be a problem
- Other: has to be able to withstand and measure liquid and gas phases

Current technology is strain gage differential pressure technology. However, these sensors are expensive, large, and fragile. Need suppliers to be engaged in product development. Motorola and EG&G might have sensors to test.

III. CIDI and SIDI Engine Sensors

A. Breakout Session - Presentation Summaries

Joseph Giachino (Visteon):

- It's possible to consider over twenty potential powertrain sensor applications including air flow, pressure (air, fuel, oil), position (valves, cams, throttle, pedals, transmission gear), speed (transmission, vehicle), torque, and oil quality
- Sensors need to be combined
- Make direct measurements of property, not an indirect measurement (e.g., measure air/fuel ratio directly)

Sensor components:
  - Sensing element

- Signal conditioning electronic
- Interface electronics
- Housing (includes connector)
- Get manufacturing people involved before starting sensor development process

Important sensor properties:

- Survivability (10 years and 150,000 miles, no cleaning or maintenance required)
- Selectivity
- Sensitivity

Sensor trade-offs:

- Accuracy
- Speed of response
- Robustness
- Span
- Cost

Richard Cernosek (Sandia National Laboratories)- "Overview of Sensor Projects at the National Laboratories"

Richard Cernosek gave an overview of the sensor activities occurring in the DOE national laboratories. There are a number of sensor development efforts underway, including:

- Vehicle exhaust gas constituent sensors
- Other gas sensors: NO_X, CO, HCs, O_2, H_2
- Particulate counters
- Pressure monitors
- Fluid monitors
- Rotation/position sensors

SNL Sensor Development

- Participant in Exhaust gas sensor CRADA: CRADA involves SNL, LLNL, and LANL. ANL is a team member under a separate CRADA. Engine testing with USCAR for use as OBD II sensors. Sandia emphasis has been on HC sensors. Acoustic wave technology for hydrocarbon monitoring using AT-cut, thickness shear mode crystals with sol-gel coatings to obtain high surface area
- Silicon MEMs pressure devices (not yet applied to automotive)
- Oil viscosity monitor using quartz resonator technique - has been tested on automobiles.
- Micromachined catalytic gas sensor: polysilicon filaments 2 microns thick by 10 microns wide … detects combustible gases

LANL Sensor Development

- Exhaust gas sensor CRADA. LANL emphasis has been on HC sensors and secondarily on CO sensors. Technology is based upon ceramic oxide sensors using zirconia and operating at 400-900 ^{o}C. “Spark plug” type design. Fast light-off. Detect H_2, CO, hydrocarbons, NO_X. 3000 hours of laboratory testing
- Lean burn oxygen sensors…linear amperometric O_2 sensors with porous metal oxide…linear response up to 25% O_2

<u>LLNL Sensor Development</u>

- Exhaust gas sensor CRADA. LLNL emphasis has been on HC sensors. New ceramic oxide electrochemical sensors for hydrocarbons using proton conducting electrolytes and differential catalysis are being developed. One-to-one response between sensor response and FID detection for hydrocarbons obtained in engine dynamometer testing. Response times on the order of 1 second and sensitivity below 25 ppm demonstrated
- Also developing a new electrochemical NO_x sensor based upon differential catalysis and ceramic oxide materials
- In past work, also investigated linear oxygen sensors and fiber optic Fabry-Perot pressure sensor

<u>ANL Sensor Development</u>

- Participant in interlab exhaust gas sensor CRADA. Use miniature ion mobility technology for hydrocarbons and NO_x . Also developing millimeter wave technology for NO_X measurement (rotational absorption of dipolar gases, compact cavity or microstrip resonators, immune to particulates or sulfur contamination)
- Has concept for ultrasonic particle monitoring system using acoustic attenuation.
- In-cylinder piezoelectric sensor for pressure monitoring

<u>ORNL Sensor Development</u>

- Developing a solid state electrochemical sensor for NO_x for lean burn gasoline engines and another for diesel

<u>PNNL Sensor Development</u>

- Aqueous tape casting system, electrochemical, novel materials design and synthesis, sensor testing and evaluation

<u>LBNL Sensor Development</u>

- Developing diesel particle scatterometer based on polarized light scattering

<u>Miscellaneous</u>

- Hydrogen gas sensor development is being conducted at SNL, LLNL, ORNL, and NREL
- Sensor arrays for vapor detection are being pursued at SNL, ANL, PNNL, and ORNL. These systems have potential use as fuel composition monitors. These monitors use pattern recognition and/or neural networks

- Numerous labs are working on non-contact rotation and position sensors such as planar Hall effect (SNL), giant magnetoresistance effect (ORNL), and rotary differential capacitance transducers (ORNL).

Paul Raptis (Argonne National Laboratory):

"Advanced Sensors for Automotive Engine Control." Areas under investigation:

- Focus on tailpipe exhaust emission sensors…ion mobility, millimeter-wave spectroscopy, acoustic and SAW/FPW chemical sensors are being pursued in the exhaust sensor CRADA
- Leak detection and location of pressurized components…micro-mass spectrometer, millimeter wave imaging, SAW
- In-cylinder sensors
- Air/fuel control system…intelligent valves
- Microwave cavity pressure sensor…deflection of diaphragm is proportional to pressure
- SAW flow sensor based on measurement of thermal conductivity change in a gas mixture
- Microwave dielectric sensor for engine oil quality monitoring
- Argonne ultrasonic viscometer…impedance and sound velocity measurements Ultrasonic particulate monitor…changes in sound velocity and acoustic attenuation
- Acoustic temperature sensor for catalytic converter which uses thin sensor materials with minimal impact on flow
- Millimeter wave proximity sensor…uses FM-CW radar technique for proximity sensing

Brage Golding, Michigan State University, NSF Center for Sensor Materials-"University Research in Automotive Sensors"

- Interdisciplinary sensor development does not fit well in an academic setting, hence the advantages of NSF multidisciplinary centers
- Air flow: wall-mounted sensor for flow rates and cumulative flow in unsteady ducts…MEMs-type device
- Hydrocarbon sensors being investigated:
  - Semiconductor MIS-Catalytic gate hydrocarbon sensor…use SiC…wide bandgap semiconductor with Pt catalytic gate-oxide barrier-SiC substrate-Pt backing layer
  - Molecular imprinting-thin, rigid polymer films via templating…expose polymer to analyte, polymerize and remove template, expose polymer template to analyte…use on SAW device to provide selective adsorption
- Oxygen sensor-inorganic chromophores for oxygen sensing in extreme environments…uses high temperature chromophores
- Fuel distribution

- Spatial and time dependent injection of fuel…can look at phase of injected species…laser induced exciplex fluorescence visualization. Tag the spray with a tracer that reports independent information about liquid and vapor phases. Optical emission is different for vapor and liquid phases. Nice visuals showing detection of fuel spray concentration 550 microseconds after injection

Frank Zhao (Daimler-Chrysler):

"Diesel Closed-Loop Control via Smoke Sensor"

- Objective : Avoid hesitation during acceleration while controlling emissions.
  - Well-known trade-off between NO_X and particulate generation.
  - NO_X always decreases with increasing EGR rate
  - NO_X and oxygen are correlated with PM, but still require some assumptions
  - Enough EGR to reach PM limit will always produce the lowest NO_X
  - PM is highly non-linear near the PM limit
  - Can provide compensation for both fuel and engine component tolerances
- Choice between in-cylinder and tail pipe sensors. Daimler-Chrysler prefers a tail-pipe sensor because it allows monitoring the behavior of all cylinders. Daimler-Chrysler also thinks a smoke/PM sensor to be more useful than NO_X sensor.
- Required PM sensor performance:
  - A highly non-linear signal change near the PM-limited A/F giving a near-digital characteristic
  - Output signal proportional to the smoke level continuous from 0 to 5 BSU (Bosch smoke units)
  - Output signal to be independent of sensor temperature or other exhaust gas components
  - Could be used as an OBD device…
    - Maximize EGR rate under all speed/load conditions subject to a PM-level constraint
    - Full load fuel control…control full load fuel via PM level feedback rather than a preset fuel quantity based on worse case conditions. Compensate for injector wear-drift over time. Altitude compensation. Minimization of effect of part-to-part variations
    - A sufficiently fast response sensor could identify cylinder-to cylinder smoke variations and compensate
    - Pilot injection function diagnostic
    - Transient sensor response could be used for tuning manifold filling models
  - Optical sensors are not acceptable…Daimler/Chrysler did some work a while back on an electrical sensor for smoke detection…apparently the sensor wasn't very reliable

Prabir Dutta (Ohio State University):

Center for Industrial Sensors and Measurements (CISM) is investigating:

- Micro-polymeric device manufacture (for life sciences application)
- Micro-ceramic device manufacture (for hostile environments)
- System integration into arrays
- Education…this is an NSF Center
- CO sensor is based on TiO_2 … anatase and rutile
- Second generation of CO sensors…selectivity through percolation
- NO sensor…planar design…electrochemical…insensitive to oxygen…use zeolite catalyst on one end of the sensor. Possible spark plug application
- Hydrocarbon sensor…electrochemical, uses a protonic conductor (sulfates and phosphates) and catalyst

Rick Soltis (Ford Research Laboratory):

Concentrating on zirconia-based NO_X Sensors

- NO_X sensors are needed for feedback control and monitoring
- Diesel engine applications
- HC injection NO_X diesel treatment
- Urea-based NO_X diesel treatment
- Feedback control
- Diagnostics (OBD for diesels)
- Operating principle: decomposing NO_X into N_2 and O_2 in low O_2 partial pressure and measuring the produced O_2 (which is proportional to NO_X) Device can also function as an oxygen sensor. Operates 750-800 ^oC. Gets similar response for NO and NO_2 with this sensor
- Issues are durability, sensitivity, selectivity (sensor responds to ammonia), poisoning by soot and sulfur, response time, cost

Dave Gardner (Nexum Research Corporation):

"Combustion monitoring through Exhaust Temperature Waveform Analysis (ETW)." Vapor temperature sensors for exhaust gases and in-cylinder usage under development. Correlated cylinder pressure waveform with exhaust temperature waveform

Harold Schock,(Michigan State University):

"Mass Airflow Sensor Studies"

- Visualization of intake system dynamics
- LDV flow measurements using a controllable oscillating flow rig
- Every unsteady flow is different…one calibration can't fit all situations
- Developing a smart sensor to make time accurate measurements of mass

flow rates in unsteady duct flows…uses silicon micro-machining
- Develop solutions to the unsteady Navier-Stokes equations

B. Sensor needs, priorities, and technical requirements

During the CIDI/SIDI breakout session sensor needs were identified through open discussion. The group then characterized the need for sensors as high, medium, or low priority. The group discussed in greater detail the requirements for the sensors that ranked highest.

Questions to answer for each proposed sensor :

- What are the technical and performance targets?
- Identify appropriateness/adequacy of current sensors.
- If a current sensor is suitable, identify improvements needed. If no current sensor is useful, how should a new sensor be developed?
- What are the barriers?
- What organizations are best suited for development, and how should organizations collaborate?
- What resources are required?
- What is the cost target?

The high priority sensor needs for CIDI/SIDI engines are NO_x and PM sensors. Wide-range oxygen sensors are medium priority. Requirements, recommendations, and issues for NO_x, PM, and wide-range oxygen sensors are described below. A summary of all CIDI/SIDI sensors discussed at the workshop is provided in Table 4.

<u>NO_x Sensors</u>

<u>Requirements:</u>

- Sensitivity requirement (diesel): 20-300 ppm (potential for some applications up to 2000 ppm feed gas)

- Measurement precision: 5 ppm

- For gas engines, sensitivity shifts to 100-200 ppm and accuracy needs to be +/- 20 ppm

- Temperature: 600-1000 ^{o}C
- Lifetime: 10 years, 150K miles (for trucks, lifetime requirement is 500K miles)

- Response time: 1 sec or less (time response must be 5 ms for cylinder-to cylinder monitoring, can be 50-100 ms for engine control)

– Separately measure NO and NO_2 (to evaluate treatments)

– Must be immune to soot, sulfur, and urea (NH_3)

Recommendations/Issues:

- NO and NO_2 need to be measured independently. Ceramic NO_X sensors based upon zirconia electrolyte are now available. Issues are sensor durability and cost (many electrical leads are required). Existing sensors are slow. Ammonia interference is a problem (this may not be a problem depending on where the sensor is located). Another big issue is the electronics - the sensors are required to measure sub micro-amps to measure low ppm concentrations. Sensor drift is a problem.

- Fundamental science is important for the ceramic-based sensor. National labs can contribute with their surface catalysis expertise. These sensors are essentially small catalytic converters, and the surface chemistry is not understood. Universities can also contribute. Prof. Göpel's group at the University of Tubingen in Germany has done some surface modeling. Perhaps some of the combustion modeling work performed by DOE labs can be extended to the NO_X sensor. The work should be pre-competitive to avoid proprietary or confidentiality issues.

- There are other potential technologies to consider, such as spectroscopic. There has also been work performed at ANL on a microwave NO_x sensor, although high cost may be an issue. There is high risk (cost and time) involved with pursuing a route other than the ceramic type NO_x sensors.

Particulate Sensors

Requirements:

– Maximum smoke number will be below 2 BSU (Bosch smoke units)

– Minimum detection: 0.2 BSU

– Response time, lifetime, and temperature requirements are the same as for the NO_x sensor

Recommendations/Issues:

- Measure total particulate mass. Industry works on Bosch number or opacity for smoke measurements rather than particle number and size distribution. Industry is more interested in particulate mass (e.g., grams per mile or grams per second) rather than particle characteristics. Integrate over all particle sizes. Different engines have different particle size distributions. Particle size determines whether the particle is retained in the human lung and the extent of health effects. The Micro-Orifice

Uniform Deposit Impactor (MOUDI) unit measures particle sizes from 0.05 to 10 microns (cascade impactor device). Linkage between Bosch number and actual particle mass loading is unclear. Particle size distribution will impact the optical attenuation (Bosch unit). PM sensor will be located either in each cylinder exhaust or at the tailpipe. A PM sensor could possibly be combined with a HC sensor.

- Industry needs to develop minimum performance requirements for the particulate sensor. The measurement can be performed optically although the sensor window will need to be baffled to avoid soot deposition on the window. Bosch smoke unit numbers need to be correlated with particle mass loading.

- There are no commercial PM sensors available for on-board measurements. The only PM sensor under development is at Argonne National Laboratory. Sensor specifications are likely to be highly engine-dependent because different engine manufacturers will have different performance specs. Improved dialogue needs to be established between auto manufacturers, sensor developers, and OEMs for development of a viable PM sensor to develop specifications such as mass loading range, time response, accuracy, and temperature range.

- Pursue two paths for development: improve the “ring-electrode” type or modify existing optical smoke measurement instrumentation (scatterometer, Bosch smoke meter, etc.) for low-cost mass production.

- Barriers to a viable PM sensor :

    - Temperature
    - Exhaust environment
    - Cost requirements
    - Lifetime, durability
    - Packaging for onboard measurement
    - Interact with auto computer to ensure sensor is “vehicle friendly”
    - Optical access…”crudding up the optical window”
    - Particle size…future smaller engines will be more difficult

- Universities and national labs could contribute to the solution to this problem, providing the base technology. A collaboration among universities national lab researchers, OEMs, and the customer (auto manufacturers) should be established.

- CARB may have role in setting sensor requirements because they must approve the measurement system based on regulatory requirements.

- The near-term introduction of diesel autos makes development of the PM sensor time critical. There may be different timetables for light-duty and heavy-duty vehicles. The market for this sensor is potentially every diesel vehicle in the world.

Wide-Range Oxygen Sensors

Requirements:

- Range is lambda from 0.7 to 15 (includes diesel)…wide range gives you better control but costs more
- Response better than 4 Hz for engine control
- Current sensors are expensive (multi-layer ceramics) - need to get cost down to $20
- Temperature range from ambient to 1000 ^{o}C (same as for NO_x sensor)
- Need fast startup time (<15 seconds)
- Resistant to poisoning from phosphorous, sulfur, lead and particulates (soot)

Recommendations/Issues:

- Wide-range oxygen sensors are too expensive because of small production quantities. Current manufacturers are Delphi, NGK Sparkplug, Bosch, and Denso (Toyota). Better sensor start-up algorithms are needed. LANL had a patent issued in 1996 for a lean-burn system which measures transfer of oxygen through thick films of transition metal oxides resistant to particulate plugging and poisoning. This sensor may only be applicable to lean burn measurements, not rich mixtures. The lean-only use may be particularly applicable to diesel engines.

- EPA should mandate tighter control on stoichiometry; otherwise lean burn O_2 sensors will continue to dominate.

- Durability for heavy-duty applications is an issue. Diesel engine manufacturers have an interest in this sensor (e.g., for identifying a bad injector or for "trimming out" injectors). Sensor can be poisoned by sulfur. Because of the high cost, the automotive systems folks have found a way to do without this sensor.

- Large resources are required to develop new sensor.

Table 4. Summary of Sensor Needs for CIDI/SIDI Engines

Sensor	Rank	State of Development/ R&D Need
NO_x	High	Electrochemical ceramic oxide sensors exist, but do not meet needs. Several efforts to improve this type of sensor underway at national labs and at sensor manufacturers. Fundamental scientific understanding needed on surface chemistry. Alternative technologies might also be looked at, but high risk (cost and time) involved in pursuing other than ceramic NO_x sensors. However, long term, high-risk projects are appropriate for national labs and universities.

PM and smoke	High	For CIDI only. Some variation in need expressed by different auto manufacturers. Need to look at in many dimensions including size and chemical properties. Minimum performance requirements need to be set. No commercial sensors exist for on-board measurement. It may be possible to further develop existing technology, but not likely. Collaborations involving national labs, universities, OEMs, and auto manufacturers needed.
Wide-range oxygen	Medium	Wide-range oxygen sensors exist but do not meet the cost constraints. Want a broadband response and not a switch, i.e. a proportional sensor. Need better sensor start-up algorithms, but need requirements specified by the systems people. Control strategies have to be developed for non-stoichiometry which utilize the fact that if you go lean you need a proportional sensor. Need dialogue between system and hardware people. Efforts should be directed at manufacturing cost reduction and robustness. Partnerships between national labs, sensor manufacturers, and auto manufacturers are needed.
Ammonia	Medium	For CIDI only and only if use urea SCR. Cannot have ammonia slip after catalyst. No sensor currently exists which meets the needs. No consensus to put a lot of resources into development of this sensor.
Hydrocarbons	Medium	No sensor available commercially which meets needs. Several efforts underway at national labs. No pressing need to initiate new efforts as long as current development work continues. However, need exists for more basic research and engineering of devices.
EGR	Medium	Current sensors exist for measuring EGR flow. Any additional needs are very system/strategy dependent.
Time-resolved exhaust temperature	Medium	Includes measurement of combustion parameters, misfire, and in-cylinder pressure. Some sensors exist. Additional needs are very system dependent.
Mass air flow	Medium	Sensors exist. Additional needs are very system dependent.
High performance torque	Medium	Good sensors really do not exist but requirements are system dependent. Need instantaneous torque.
Fuel composition	Low	Little interest in sensors for fuel composition or volatility.
Carbon monoxide	Low	Only needed for fuel cells, not much for CIDI/SIDI.
Sulfur content in fuel	Low	No need seen for sensors. R&D need is how to get sulfur out.

It was noted that there are suppliers developing in-cylinder pressure sensors and torque sensors and that both of these are very system/strategy dependent. However, the group expressed no interest in developing an in-cylinder pressure sensor. In addition, a better resolution crankshaft position sensor was discussed, with limited interest.

While many of the sensors identified above currently exist for defined applications, it is the consensus that there are no sensors available that fall into the highest need category and meet the combination of specifications required by the automotive industry. These specifications include operation in very harsh environments, high sensitivity and selectivity, long lifetime, low/no maintenance, high stability, and low cost, among others. For PM sensors noted deficiencies are: durability, operation at high temperature, cost, and the tendency of window to foul. NO_x sensors currently exist, but they are too complex and costly. Basic understanding of surface chemistry is needed. One particular theme which appeared to run through much of the discussion in the CIDI/SIDI session was that sensors need to be developed for specific systems, not generic operation, due to differences in manufacturers' measurement strategies.

Appendices

A. List of Participants

B. Agenda

C. Visual Aids from Technical Presentations

Plenary Session

- **Overview of the DOE Transportation Fuel Cell Program-JoAnn Milliken**
- **Sensor Performance Requirements for Compression-Ignition, Direct-Injection Engines-Ken Howden**
- **Spark Ignition Direct Injection Engine R&D-Rogelio Sullivan**
- **Driving Towards Clean Air: Countdown to Zero-Tom Cackette**
- **State of Development of PEM Fuel Cells-Doug Wheeler**
- **State of Development-CIDI Engines-Rich Belaire**
- **Sensors: An Overview-Joseph Stetter**

Fuel Cells Session

- **A Critical Look at the Maturing Development and Utilization of Optical Sensor Technologies-Jacob Wong**
- **Gas Sensors for Fuel Cell Process Monitoring-Shuh-Haw Sheen**
- **Sensor Functions in Fuel Cells-Doug Wheeler**

CIDI/SIDI Session

- **Review: National Laboratory Sensor Projects for CIDI/SIDI Engines-Richard Cernosek**
- **Sensor Priorities from a Supplier Standpoint-Joe Giachino**
- **University-Based Sensor Research-Brage Golding**

- **Real-Time Sensors for Intelligent Control of Automotive Engines and Processes-A. C. Paul Raptis**

- **Diesel Closed-Loop Control Via Smoke Sensor-Frank Zhao**

- **Ford Motor Company Sensor Program-Rick Soltis**

Appendix A: List of Participants

Participants DOE Sensors Workshop, Jan. 25-26, 2000

C. Abe
NGK Spark Plug Mfg.
46929 Magellan Dr.
Wixom MI 48393
248-926-6900 Fax 248-926-6910
E-mail Add: csuh@ngkmfg.com

Shabbir Ahmed
Argonne Natl. Lab, Chemical Tech. Div.
9700 South Cass Ave, Bldg. 205
Argonne IL 60439
630-252-4553 Fax 630-972-4553
E-mail Add: ahmed@cmt.anl.gov

Richard A. Alderman
Honeywell
11 W. Spring St.
Freeport IL 61032
815-235-6828 Fax 815-233-2761
E-mail Add: RAlderma@micro.honeywell.

Brian Anderson
Westinghouse Savannah River Co.
Bldg. TBA B-140
Aiken SC 290808
803-725-1421 Fax 803725-2756
E-mail Add: brian02.anderson@srs.gov

Richard C. Belaire
Ford Motor Company
Scientific Research Laboratory
Dearborn MI 48121-2053
313-845-9353 Fax 313-337-5571
E-mail Add: rbelaire@ford.com

Bruce Bishop
CeraMem Corp.
12 Clematis Avenue
Waltham MA 02453
781-899-4495 X30 Fax 781-899-6478
E-mail Add: bishop@ceramem.com

Ulrich Bonne
Honeywell Technology Center, 4B55
12001 State Highway 55
Plymouth MN 55441-4799
612-954-2758 Fax 612-954-2504
E-mail Add: bonne_ulrich@htc.honeywe

Eric Brosha
Los Alamos National Laboratory
MS 0429 MST-11, Electronic Matls & Device
Los Alamos NM 87545
505-665-4008 Fax 505-665-4292
E-mail Add: brosha@lanl.gov

Tom Cackette
California Air Resources Board
2220 L Street
Sacramento CA 95814
916-322-2892 Fax 916-322-6003
E-mail Add: tcackett@arb.ca.gov

Robert W Carling
Sandia National Laboratories
P. O. Box 969, MS 9053
Livermore CA 94551-0969
925-294-2206 Fax 925-294-1004
E-mail Add: rwcarli@sandia.gov

Participants DOE Sensors Workshop, Jan. 25-26, 2000

Richard Cernosek
Sandia National Laboratories
P.O. Box 5800, MS 1425
Albuquerque NM 87185-1425
505-845-8818 Fax 505-845-1198
E-mail Add: rwcerno@sandia.gov

Trevor N. Demayo
UCI Combustion Lab, UC, Irvine

Irvine CA 92697-3550
949-824-5950, X2 Fax 949-824-7423
E-mail Add: tnd@ucicl.uci.edu

Brandon W Chung
LLNL
7000 East Ave, L-350
Livermore CA 94550
925-423-3896 Fax 925-422-6892
E-mail Add:

Robert W Dibble
Univ. of California at Berkeley
Dept. of Mechanical Engr.
Berkeley CA 94720
510-642-4901 Fax 510-642-1850
E-mail Add: dibble@Newton.berkeley.ed

Roland Cuenca
Argonne National Lab.
9700 S. Cass Avenue
Argonne IL 60439
630-252-9175 Fax 630-252-3443
E-mail Add: rcuenca@anl.gov

Steven Dieckman
Argonne National Laboratory
9700 Cass Ave.
Argonne IL 60434
630-252-5628 Fax 630-252-3250
E-mail Add: dieckman@anl.gov

Patrick B. Davis
U.S. DOE, Office of Adv. Auto. Tech.
1000 Independence Ave, SW,
Washington DC 20585
202-586-8061 Fax 202-586-9811
E-mail Add: patrick.davis@ee.doe.gov

Kanda Swamy Durai-Swamy
Hydrogen Burner Technology, Inc.
3925 East Vernon Street
Long Beach CA 90815
562-597-2442 X51 Fax 562-597-8780
E-mail Add:

William J. Dawson
NexTech materials, Ltd.
720-I Lakeview Plaza Blvd.
Worthington OH 43085
614-842-6606 Fax 614-842-6607
E-mail Add: dawson@nextechmaterials.c

Prabir K. Dutta
Ohio State University, Dept. of Chemistry
120 W. 18th Avenue
Columbus OH 43210
614-292-4532 Fax 614-292-1685
E-mail Add: Dutta.1@osu.edu

Participants DOE Sensors Workshop, Jan. 25-26, 2000

Kathleen P. Epping
Dept. of Energy, Forestall Bldg.
1000 Independence Ave. SW
Washington DC
202-586-7425 Fax 202-586-4617
E-mail Add: Kathi.Epping@hq.doe.gov

Robert Glass
LLNL
P. O. Box 808, L-644
Livermore CA 94550
925-423-7140 Fax 925-423-7149
E-mail Add: glass3@llnl.gov

Qinbai Fan
Institute of Gas Technology
1700 South Mount Prospect Rd.
Des Plaines IL 60018-1804
847-768-0812 Fax 847-768-0916
E-mail Add: qfan@igt.org

Brage Golding
Michigan State University
305 Physics/Astronomy Bldg.
East Lansing MI 48824-1116
517-355-9708 Fax 517-432-5501
E-mail Add: golding@pa.msu.edu

David P. Gardiner
Nexum Research Corporation
615 Norris Court
Ontario CA K7P 2R9
613-384-7894 Fax 613-384-1604
E-mail Add: nexum@fox.nstn.ca

Ichiro Gonda
NGK Spark Plug
6 46929 Magellian Dr.
Wixom MI 48393
248-926-6900 Fax 248-926-6910
E-mail Add:

Fernanado Garzon
Los Alamos National Laboratory
MST-11
Los Alamos NM 87545
505-667-6643 Fax 505-665-4292
E-mail Add: garzon@lanl.gov

Eugene Gonze
GM Proving Ground
Mail Code: 483-331-500
Milford MI 48380-3726
248-676-1881 Fax 248-676-1808
E-mail Add: eugene.v.gonze@gm.com

Joseph M. Giachino
Ford Motor Company
ETC/C490
Dearborn MI 48121-2053
313-390-2841 Fax 313-323-6630
E-mail Add: jgiachin@visteon.com

Jeffrey W Griffin
Battelle Pacific Northwest National Lab
PO Box 999, MS K5-17
Richland WA 99352
509-375-2081 Fax 509-372-4725
E-mail Add:

Participants DOE Sensors Workshop, Jan. 25-26, 2000

Craig Habeger
Battelle Pacific Northwest National Lab.
P. O. Box 999, K2-44
Richland WA 99353
509-575-2201 Fax 509-375-2186
E-mail Add: craig.habeger@nl.gov

Scott Alan Hutzler
Southwest Research Institute
6220 Culebra Rd.
San Antonio TX 78228
210-522-6978 Fax 210-522-3270
E-mail Add: shutzler@swri.edu

Jeff Haslam
LLNL
PO Box 808, L-353
Livermore CA 94550
925-423-6989 Fax 925-423-7390
E-mail Add: haslam5@llnl.gov

N. I'Shida
NGK Spark Plug Mfg.
46929 Magellan Dr.
Wikom MI 48393
248-926-6900 Fax 248-926-6910
E-mail Add:

Simone Hochgreb
Sandia National Laboratory
MS 9053
Livermore CA 94550
925-294-4724 Fax 925-294-1004
E-mail Add: scochgr@sandia.gov

Michael A. Inbody
Los Alamos National Laboratory
P. O. Box 1663 MS J-576
Los Alamos NM 87545
505-665-7853 Fax 505-665-9507
E-mail Add: inbody@lanl.gov

Kenneth C. Howden
U.S. Department of Energy
EE-32
Washington DC 20585
202-586-3631 Fax
E-mail Add: ken.howden@hq.doe.gov

Edward A. Johnson
Ion Optics, Inc.
411 Waverley Oaks Rd., Suite 144
Waltham MA 02452
781-788-8777 X101 Fax 781-788-8811
E-mail Add: ejohnson@ion-optics-com

Arlon J. Hunt
Lawrence Berkeley National Lab.
70-108
Berkeley CA 94720
510-486-5370 Fax 510-486-7303
E-mail Add: ajhunt@lbl.gov

Valerie Ann Jordan
Ford Motor Company
P. O. Box 6010 MD 11170
Dearborn MI 48121
313-323-0553 Fax 313-323-1129
E-mail Add: vjordan1@ford.com

Participants DOE Sensors Workshop, Jan. 25-26, 2000

Michael D. Kass
Oak Ridge National Laboratory
P. O. Box 2009, VBldg. 9108, MS 8088
Oak Ridge TN 37831-8088
865-576-8323 Fax 865-574-2101
E-mail Add: ymy@ornl.gov

Jim Merritt
DOE
Forrestal Bldg, Rm. 5G-064, EE-32
Washington DC 20585
202-586-0903 Fax
E-mail Add:

Donald E. Keski-Hynnila
Detroit Deisel Corporation
13400 Outer Drive West
Detroit MI 48239-4001
313-592-7568 Fax 313-592-7940
E-mail Add: donald.keski-hynnila@detroi

JoAnn Milliken
US Dept of Energy-HQ, Office of
Transp. Tech, SW, EE-32
Washington DC 20585
202-586-2480 Fax 202-586-9811
E-mail Add: joann.milliken@hq.doe.gov

Di-Jia Liu
Honeywell International Inc.
50 E. Algonquin Road
Des Plaines IL 60017
847-391-3703 Fax 847-391-3750
E-mail Add: di-jia.liu@AlliedSignal.com

Barbara S. Moore
General Motors - Gloal Alternative
Center
Honeoye Falls NY 14472
716-624-6617 Fax 716-724-6680
E-mail Add: barbara.moore@gm.com

Darby B. Makel
Makel Engineering Inc.
1020 Marauder Street, Suite D
Chico CA 95973
530-895-2771 Fax 530-895-2777
E-mail Add: dmakel@markelengineering.

Patricia J. Nelson
General Motors
10 Carriage Street
Honeoye Falls NY 14472
716-624-6690 Fax 716-624-6680
E-mail Add: patricia.j.nelson@gm.com

Ralph McGill
Oak Ridge Natinal Laboratory
P. O. Box 2009, MS-8087
Oak Ridge TN 37831
865-574-4077 Fax 865-574-2102
E-mail Add: r9m@ornl.gov

Ronald S Patrick
ECM Engine Control & Monitoring
586 Weddell Dr., Unit 2
Sunnyvale CA 94089
408-734-3433 Fax 408-734-3432
E-mail Add: ecmco@earthlink.net

Participants DOE Sensors Workshop, Jan. 25-26, 2000

Ai Quoc Pham
LLNL
7000 East Ave, L-231
Livermore CA 94550
408-383-9195 Fax 422-1364
E-mail Add: Emp 700506,

Tim J. Rehg
Allied Signal
P. O. Box 2960
Torrance CA 90504
310-512-2281 Fax 310-512-4128
E-mail Add:

Jeff Pickles

234 Jefferson Street
Klamath Falls OR 97601
541-882-4206 Fax
E-mail Add: picklesj@oit.edu

Phillip N. Ross, Jr.
Lawrence Berkekely Natl. Lab., Matls Dept.
One Cyclotron Road
Berkeley CA 94720
510-486-6226 Fax 510-486-5530
E-mail Add: pnross@lbl.gov

Bill Pitts
NIST, Natl. Inst. of Standards & Technology
100 Burcan Drive, Mail Stop 8653
Gaithersburg MD 20899-8653
301-975-6486 Fax 301-975-4052
E-mail Add: wpitts@nist.gov

Michael J. Royce
DaimlerChrysler Corp.
CMS: 482-01-07, 800 Chrysler Drive
Auburn Hills MI 48326-2757
248-576-4996 Fax 248-576-2182
E-mail Add: mjr8@daimlerchrysler.com

David B. Quinn
Delphi Automotive Systems
1601 N. Averill Avenue
Flint MI 48556
810-257-5036 Fax 810-257-5709
E-mail Add: david.quinn@delphiauto.co

Jennifer W Rumsey
EPYX/Arthur D. Little
20 Acorn Park, 32/107
Cambridge MA 02140
617-498-6753 Fax 617-498-6656
E-mail Add: rumsey.jennifer@adlittle.com

Paul C. Raptis
Argonne National Laboratory
9700 S. Cass Ave
Argonne IL 60439
630-252-5930 Fax 630-252-3250
E-mail Add: raptis@anl.gov

Harold Schock
Michigan State University
Engine Research Laboratory
East Lansing MI 48824-1116
517-353-9328 Fax 517-432-3341
E-mail Add: schock@egr.msu.edu

Participants DOE Sensors Workshop, Jan. 25-26, 2000

Shuh-Haw Sheen
Argonne National Laboratory
9700 S. Cass Ave., Bldg. 308
Argonne IL 60439
630-252-7502 Fax 630-252-3250
E-mail Add: sheen@anl.gov

Joseph R. Stetter
Illinois Institute of Technology
BCPS Department, Life Sciences Bldg.
Chicago IL 60616-3793
312-567-3443 Fax 312-567-3494
E-mail Add: stetter@iit.edu,SSN

Carol Smith
Ford Motor Co.
2000 Rotunda
Dearborn MI 48121-2053
313-322-7765 Fax 313-248-5075
E-mail Add: csmith20@ford.com

Kathryn Ann Striebel
Lawrence Berkeley Natl. Lab.
1 Cyclotron Road
Berkeley CA 94720
510-486-4385 Fax 510-486-7303
E-mail Add: kastriebel@lbl.gov

James R. Smith
LLNL
P. O. Box 808, L-644
Livermore CA 94550
925-422-5196 Fax 925-423-7914
E-mail Add: jrsmith@llnl.gov

Chung Suh
NGK Spark Plug Mfg.
46929 Magellan Dr.
Wikom MI 48993
248-926-6900 Fax 248-926-6910
E-mail Add: csuh@ngkmfg.com

Richard Soltis
Ford Motor Co.
MD 3028/SRL, 20000 Rotunda Drive
Dearborn MI 48121
313-323-1708 Fax 313-322-7044
E-mail Add: rsoltis@ford.com

Rogelio Sullivan
Dept of Energy, Forestal Bldg., EE-32
Off of Adv Automotive Tech, MS 6A-116,
Washington DC 20585
202-586-8042 Fax
E-mail Add: Rogelio.Sullivan@hq.doe.g

Steve Stein
Battelle Seattle Research Center
4500 Sand Point Way NE
Seattle WA 98105
206-528-3340 Fax 206-528-3325
E-mail Add: stein@battelle.org

Scott Swartz
Next Tech Materials
720-I Lakeview Plaza Blvd.
Worthington OH 43085
614-842-6606 Fax 614-842-6607
E-mail Add: swartz@nextechmaterials.co

Participants DOE Sensors Workshop, Jan. 25-26, 2000

Jimmy Dean Thornton
U.S. Dept. of Energy, FETC
P. O. Box 880
Morgantown WV 26507-0880
304-285-4427 Fax 304-285-4469
E-mail Add: jthorn@fetc.doe.gov

Douglas J. Wheeler
International Fuel Cells, Technology Dept.
195 Govenor's Highway
South CT 06074
860-727-2513 Fax 860-727-2750
E-mail Add: wheeled@ifc.utc.com

Tim Toepfer
Plug Power
968 Albany Shakes Road
Latham NY 12110
? Fax 518-782-7909T
E-mail Add: tim_toepfer@plugpower.co

Jacob Y. Wong
Ion Optics, Inc.
7127 Hollister Ave., Ste #9
Goleta CA 93117
? Fax 805-685-0555
E-mail Add: jacobwong@earthlink.net

John William Van Zee
University of South Carolina
Dept. of Chemical Engineering
Columbia SC 2208`
803-777-2285 Fax 803-777-8265
E-mail Add: vanzee@engr.sc.edu

Steve Woodruff
Federal Energy Technology Center
PO Box 880, MS N05
Morgantown WV 26507-0880
304-285-4175 Fax 304-285-4403
E-mail Add: swoodr@fetc.doe.gov

Jud W Virden
Pacific Northwest Natl. Lab.
P.O. Box 999
Richland WA 99352
509-375-6512 Fax 59-375-2186
E-mail Add: jud.virden@pnl.gov

Fuquan (Frank) Zhao
Daimlerchrysler
800 Chrysler Drive
Auburn Hills MI 48326
248-576-5101 Fax 2 48-576-2205
E-mail Add: fz3@daimlerchrysler.com

Jaco Visser
Ford Motor Co.
MD 3028 / SRL
Dearborn MI 48121-2053
313-845-0101 Fax 313-322-7044
E-mail Add: jvisser@ford.com

Appendix B: Agenda

Agenda for Sensors for Fuel Cells and CIDI/SIDI Engines Workshop

<u>Day 1 (January 25, 2000)</u>

7:00-8:00 Registration and Continental Breakfast

Plenary Session (Group)

8:05-8:15 Welcome, Workshop Opening-Robert Glass, Chairperson

8:15-8:35 Overview of the DOE Fuel Cells for Transportation Program-JoAnn Milliken (DOE)

8:35-8:55 Overview of the DOE CIDI Engine Program-Ken Howden (DOE)

8:55-9:15 Overview of the DOE SIDI Engine Program-Rogelio Sullivan (DOE)

9:15-9:45 Future Emissions Regulations-Thomas Cackette (California Air Resources Board)

9:45-10:15 Break

10:15-10:45 Technical Overview-State of Development of PEM Fuel Cells-Doug Wheeler (International Fuel Cells)

10:45-11:15 Technical Overview-State of Development of CIDI Engines-Richard Belaire (Ford)

11:15-11:45 Sensors Overview-Joseph Stetter (Illinois Institute of Technology)

11:45-1:00 Lunch

1:00-3:00 Parallel Breakout Work Sessions

Work Group 1: CIDI/SIDI engine sensors

Work Group 2: Fuel Cell and Reformer Sensors

A panel will be formed to technically coordinate the discussions. The panel will consist of one member representative from each of the following: national labs, universities, sensor manufacturers (or sensor researcher from automobile companies), CIDI engine/SIDI engine developers/emission controls (or PEM fuel cell/fuel reformer developers).

Each member of the panel will be given 15 minutes for a introductory overview technical talk outlining work underway (the national labs and university people will cover the breadth of work in these two areas), concentrating on the technical issues to set the stage for the following brainstorming sessions.

Groups work to: (1) identify the requirements for sensors; (2) set R&D priorities; (3) identify the technical targets and technical barriers, and, (4) formulate R&D plans

A facilitator will be assigned to each group.

3:00-3:20	Break
3:20-5:00	Continue Discussions
6:00	No Host Reception
7:00	Dinner with speaker (TBD)

Day 2 (January 26, 2000)

7:00-8:00 Continental Breakfast

8:00-8:05 (Group) Chairperson's welcome back and charge to groups

8:05-10:00 Continue Breakout Work Sessions

Work Group 1: CIDI/SIDI engine sensors

Work Group 2: Fuel Cell sensors

Same panels and facilitators for the two groups as Tuesday. Groups continue on with discussions started yesterday. In the latter half of this session groups will focus on evaluating resources needed for success.

10:00-10:20 Break

10:20-11:30 Continue Discussions in Breakout Work Groups

Groups will focus on outlining the mechanisms for collaborations in R&D and sensor testing at automobile companies and fuel cell developers with possibility of pre-competitive sharing of data.

11:30-12:30 Reconvene as group and report out

Spokesperson from each group will report on prioritized R&D list, technical targets and barriers, R&D plans, collaborative plans, and ideas on how sensor data can be shared.

12:30 Adjourn/Discussion of next steps and workshop products/lunch

Appendix C: Visual Aids from Technical Presentations

Plenary Session

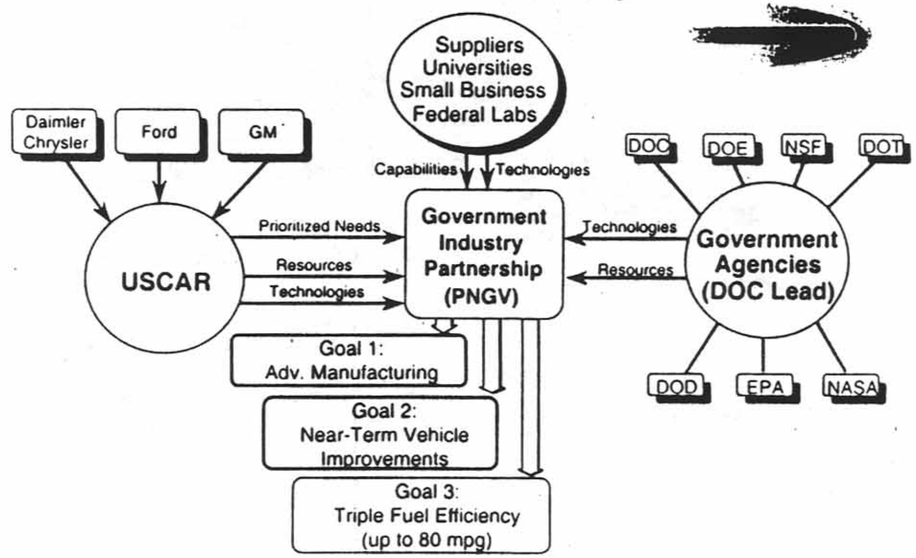
Program Overview

Department of Energy
Transportation Fuel Cell Program

JoAnn Milliken, Donna Ho, Pat Davis, Steve Chalk

Sensor Workshop
January 25-26, 2000
Berkeley, CA

The Partnership for a New Generation of Vehicles

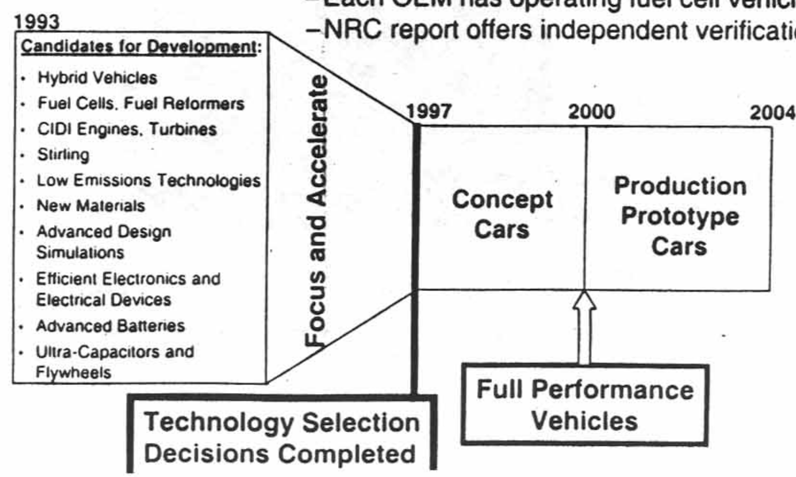


Agenda

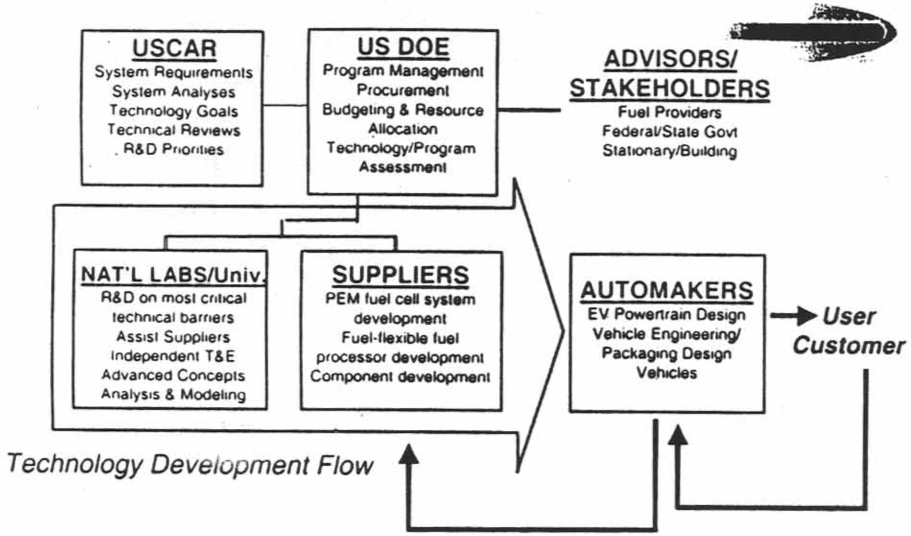
- **Partnership for a New Generation of Vehicles**
- **Transportation Fuel Cell Program**
  - ➩ **Implementation Strategy**
  - ➩ **Fuel Strategy**
  - ➩ **Technical Challenges**
  - ➩ **Projects/Budget**
  - ➩ **Recent Technical Accomplishment**
  - ➩ **Sensor Requirements**

Timetable for PNGV

Remarkable Progress Achieved in S[illegible]s
- Each OEM has operating fuel cell vehicles
- NRC report offers independent verification



Fuel Cell Program Implementation A Strategic Partnership

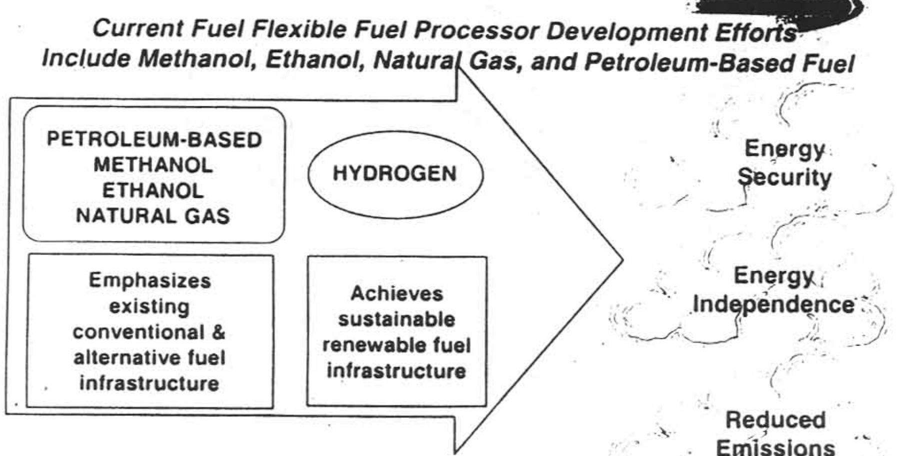


Integrated Fuel Cell Power Systems - Technical Targets

Characteristic	PNGV Targets
Energy efficiency @ 25% peak power	48%
Power density	300 W/l
Specific power	300 W/kg
Cost	$50/kW
Start-up to full power	0.5 min
Transient response (from 10 to 90% power)	10 sec
Emissions	<Tier 2
Durability	5000 hours

Year 2004 targets using gasoline (including fuel processor, stack, and auxiliaries; excluding gasoline tank and DC-DC converter).

DOE Fuel Strategy for Fuel Cells



DOE to publish draft Advanced Petroleum-Based Fuels Program Plan for industry comment (early 2000)

Systems Analyses Identify Component and Operating Challenges to Meet Program Targets

Meeting system efficiency targets presents the following challenges

	Power Level, Net	
	50 kW	12.5 kW
Cell Voltage, V	0.772	0.896
Current Density, mA/cm^2	680	139
Fuel Utilization, %	85	85
Operating Pressure, atm	3	1.6
Efficiency, Compressor, %	75	65
Efficiency, Expander, %	90	80
Efficiency, Fuel Processor, %	80	80
Efficiency, Stack Subsystem, %	48	60
Efficiency, Total System, %	38	48

Note: Using Petroleum-based Fuel

Fuel-Flexible Fuel Cell System

..... Technical Barriers

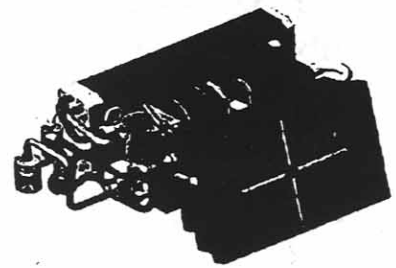
System	Fuel Processor	Stack Subsystem Components
• Efficiency • System Integration - Volume/Weight - Thermal/Water Management - Cost Trade-offs • Balance of Plant Components ⇒ **Sensors/Controls**	• Fuel Processor Start-up & Transient Operation • Fuel Processor Durability & Emissions • Catalyst Cost • CO Clean-Up • Fuel Processor System Integration & Efficiency	• Cost of Stack Components • Cathode Performance • Stack Durability • Air Systems • CO Tolerance

CY 2000 Plans Major System Deliverables

Two 50 kW Stack Systems:

AlliedSignal Aerospace Equipment Systems

Energy Partners

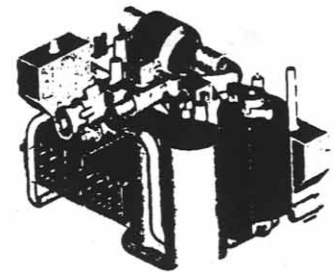


EP 50 kW_{net} Automotive System

Two 50 kW Integrated Systems:

Plug Power (pressurized)

International Fuel Cells (near ambient)



IFC Conceptual 50 kW Powerplant

Projects and Funding by Budget Category

Systems	Fuel Processing	Stack Subsystem Components
• Plug Power/Epyx • IFC • Energy Partners, AlliedSignal • ANL	• Epyx • Hydrogen Burner • McDermott • Plug Power/UOP • AlliedSignal • Arcadis • ANL, LANL, PNNL	• Energy Partners, AlliedSignal, IFC, Plug Power • IGT, Electrochem • 3M, SwRI/Gore, Foster-Miller • Vairex, A.D. Little, AlliedSignal, Meruit • Spectracorp • LANL, LBNL
FY99: $5.75M **FY00: $6.0M**	**FY99: $13.0M** **FY00: $14.5M**	**FY99: $14.9M** **FY00: $14.0M**

Key Challenges

- *Efficiency*
  - *Cathode Performance*
  - *Air Management*
- *Fuel processor performance/size*
- ⇒ *Sensors and Controls*
- *Cost*

Fuel Cell Sensors Objectives - 1998

- Develop sensors/detectors to identify and measure chemical species
  - ⇨ CO, H_2, H_2S, hydrocarbons
- Develop sensors/detectors to identify operating conditions
  - ⇨ mass flow rates, humidity, temperature, pressure

Current Sensor Projects

Low-Cost Carbon Monoxide and Hydrogen Sensors
- Illinois Institute of Technology
(Joseph Stetter)

Objective: Develop advanced-design amperometric gas sensors for automotive fuel cell applications

Fuel Cell Sensors Requirements - 1998

- CO sensor: 10-200 ppm, 0.2 seconds, in the gas mixture entering the fuel cell stack
- CO sensor: 0.1-20%, 0.2 seconds
- H_2 sensor: 1-100% , 0.2 - 2 seconds
- Differential H_2 sensor: H_2(in) - H_2(out)
- Reactive Hydrocarbon sensor: 0-5000 ppm)
- Reactive Sulfur sensor: 0-100ppm
- Gas temperatures: 20-1200C
- Coolant conductivity: <10micromho
- Electrical output capable of driving a control system
- Durability ⇨ 5,000 hours
- Low-Cost ⇨ $50/kW system cost

Workshop Objectives

- Identify sensor requirements and technical targets for automotive PEM fuel cell systems operating on reformed fuels
- Outline a prioritized research and development plan which includes industry, national lab, and university participation

DOE Sensor Workshop

CIDI Combustion and Emission Control R&D

Sensor Performance Requirements for Compression-Ignition, Direct-Injection Engines

Kenneth C. Howden
Program Manager
Office of Advanced Automotive Technologies
Office of Transportation Technologies
Office of Energy Efficiency and Renewable Energy

Emission Control Technology Update Overview

CIDI Combustion and Emission Control R&D

- PNGV CIDI Combustion / Emission Control Overview
- LEP/DOE National Laboratory CRADAs
  - Lean NOx Catalysis
  - Non-Thermal Plasma
- Emission Control Subsystem Cooperative Agreements
  - Cummins / Engelhard
  - Detroit Diesel / Johnson Matthey
- Response to proposed EPA Tier 2 Requirements

CIDI Program Technologies

CIDI Combustion and Emission Control R&D

CIDI ENGINE TECHNOLOGY + **EMISSION CONTROLS** =

CIDI Engine Technology
- *Combustion improvements for reduced emissions & improved fuel economy*
- *Exhaust Gas Recirculation (EGR)*
- *Reformulated Fuels*
- *Modeling*

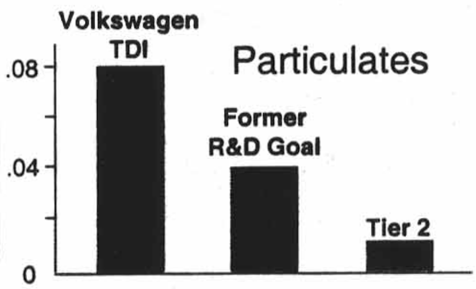
NOx
- *Lean-burn catalysts*
- *NOx Traps*
- *Non-thermal Plasma*
- *Selective Catalytic Reduction*

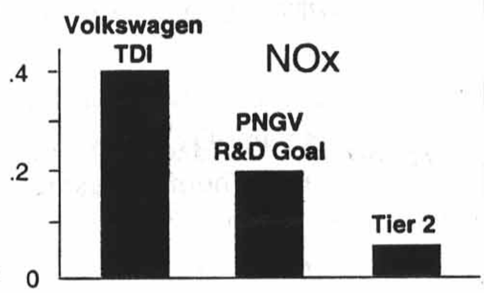
Particulates
- *Regenerative PM Traps*
  - *Catalytic*
  - *Microwave*

Technologies which enable 3X passenger car fuel economy & near zero emissions (0.01g/mi PM and 0.05 g/mi NOx) and higher light truck fuel economy

Major Technical Barriers: Particulate and NOx Goals (grams/mile)

CIDI Combustion and Emission Control R&D





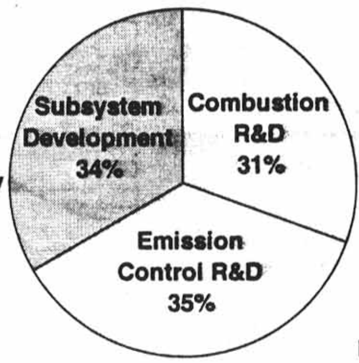
- These goals are very difficult to achieve simultaneously
- Requires development of cleaner combustion, advanced emission controls, and new fuel formulations

Combustion and Emission Control R&D FY2000 Budget ($14.654M)

CIDI Combustion and Emission Control R&D

Cummins / Engelhard

DDC / Johnson Matthey



Sandia Livermore
Argonne
Ford

Oak Ridge
Pacific Northwest
Los Alamos
Lawrence Berkeley
Sandia Albuquerque

Common Requirements for Hydrocarbon and NO_x Sensors

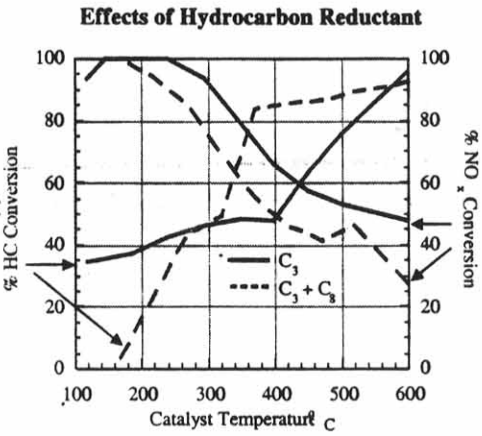
CIDI Combustion and Emission Control R&D

Minimum Concentration Sensitivity and Range	5 PPM 0-2000 PPM C_1 0-1000 PPM Nitrogen Oxide
Accuracy and Resolution	On the order of minimum sensitivity
Production Sample Performance Variability	No post-production calibration for sensor or control unit.
Physical Parameters	Size, weight, power consumption, and voltage of O_2 sensor
Transient response / power-on stabilization	1 second
Cross Sensitivity	Immune to O_2 CO H_2 H_2O
Deactivation	Insensitive to fuel and oil additives and impurities
Flow and Pressure Variation Sensitivity	Output signal independent of ambient air flow and pressure
Temperature Endurance and Linearity	Must withstand temperature range of – 40 to +1000 C with linearity within minimum sensitivity
Characteristic Life	10 years or 120,000 miles
Cost	$10 to $20 per unit in mass production (1 million / year)

LEP Lean NOx Catalyst Program
Activity of New LANL Formulation

CIDI Combustion and Emission Control R&D

- More aggressive NOx standard proposed to be 0.05 g/mi - requires 90-95% NOx conversion over FTP
- Newly discovered formulation has generated industry interest
- Over 90% conversion over large temperature window under ideal test conditions
- Intellectual property issues being addressed to accelerate technology transfer.
- OEMs performing additional evaluations to validate performance

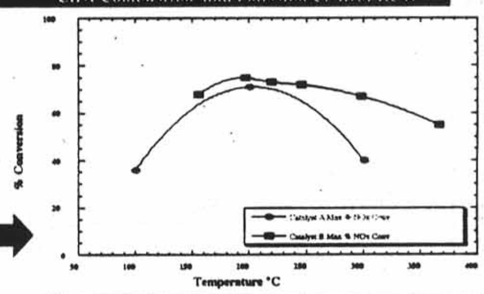


Non-Thermal Plasma for NOx Reduction
LEP CRADA Program

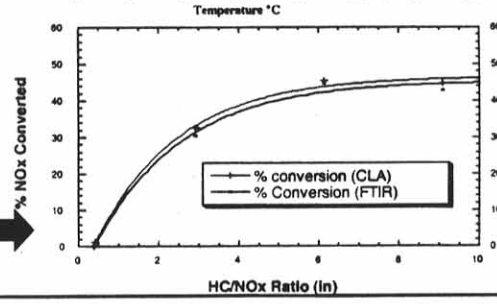
CIDI Combustion and Emission Control R&D

Full-scale, two-stage plasma catalyst system tested in simulated and actual CIDI exhaust stream

- Achieved NOx conversion of 70% during extended periods with 50 ppm SO_2 lab gas mixture and propylene reductant



- Achieved 45% NOx conversion in VW TDI exhaust stream with reductant during ORNL testing



New Industry CIDI Emission Control Subsystem Cooperative Agreements

CIDI Combustion and Emission Control R&D

- NRC review of CIDI program recommended greater industry involvement

- Two Emission Control Subsystem contractor teams selected from competitive solicitation:
  - Cummins Engine Company - Engelhard.
  - Detroit Diesel Corporation - Johnson Matthey

- Awards made in September 1999 for 2 1/2 year efforts (later extended to 3 years due to funding shortfall)

Emission control subsystems will be scalable from PNGV to Light Truck applications

Emission Control Subsystem Projects: Performance Goals

CIDI Combustion and Emission Control R&D

Deliverables:

- Complete Emission Control Subsystems for PNGV / LDT engines in Sep '02.
- Final report documenting design with engine-and tailpipe-out exhaust gas speciation over FTP.

	Cummins	DDC
Tailpipe NOx	0.20 g/mi	0.14 g/mi
Tailpipe PM	0.018 g/mi	0.02 g/mi
Emission Control Cost	$ 4.50 / kW	
Durability	> 4250 hrs	
Volume	< 20 liters	
Weight	< 16 kg	

NOx goals are less than or equal to PNGV 2004 target. All other goals are intermediate values between PNGV-established 2000 and 2004 targets.

Cummins Engine Company Technical Approach

CIDI Combustion and Emission Control R&D

- Several parallel prototype hardware combinations for reducing NO_x and PM to be developed with Engelhard
  - selective catalytic reduction (SCR) with urea
  - plasma-assisted catalyst
  - lean NO_x catalyst
  - adsorber catalyst using intermittent rich conditions
- Each system to include a microwave-regenerated catalyzed soot filter for PM
- Engine system-level demonstrations on PNGV Ford DIATA 1.3 liter (hardware deliverables) and Cummins/DOE Light Truck 4-liter V6

Detroit Diesel Corporation Technical Approach

CIDI Combustion and Emission Control R&D

- Verification on DDC/Chrysler 1.46 liter, 3-cylinder, 55kW PNGV hybrid engine (hardware deliverable)
- Scaled to demonstrate on DDC 4.0 Liter V6 developed under DOE OHVT Light Truck Engine program (hardware deliverable)
- Vehicle level demonstration on two PNGV Neons and one Durango SUV
- Johnson Matthey using three NO_x reduction approaches - Selective Catalytic Reduction (Urea SCR), NO_x catalyst and lean NO_x trap
- Johnson Matthey Continuously Regenerating Trap for PM reduction

Target Areas for Possible FY2001 Budget Increase

CIDI Combustion and Emission Control R&D

- Accelerate Advanced Emission Control Subsystems R&D with DDC & Cummins towards meeting ultimate Tier 2 standards
- Increase LEP/DOE national laboratory efforts to resolve high risk barriers associated with SCR, LANL NOx catalyst and Non-thermal plasma
- Initiate sensor technology efforts with LEP, national laboratories and major suppliers
- Accelerate Sandia optical access engine and EGR research, Argonne fuel injection X-ray measurements, and Oak Ridge engine-based emission control system analysis

CIDI Program Accelerated and Focussed in Response to Proposed Tier 2 Regulation

CIDI Combustion and Emission Control R&D

- Initiated cooperative R&D agreements with diesel engine manufacturers and their catalyst suppliers
- Coordinated light- and heavy-duty programs to leverage resources
- Integrating advanced petroleum-based fuels program with combustion and emission control program

SPARK IGNITION DIRECT INJECTION ENGINE R&D

DOE/LLNL Sensor Workshop

Rogelio Sullivan

Berkeley, CA
January 2000

Presentation Outline

- SIDI R&D program overview
- Sensor for SIDI engines

1

SIDI R&D Program

- **FY 1999 new start**
  - **$7 M FY 2000 appropriation**
  - **Coordination through USCAR's Low Emission Partnership (LEP)**
- **Objectives**
  - **Conduct research to enable SIDI systems**
  - **Supporting technology development for emission control**
- **Four program thrusts**
  - **Emission sensor development (LEP CRADAs)**
  - **Fundamental combustion & modeling (Sandia & Universities)**
  - **Engine and component research (ORNL, ANL)**
  - **Component development (Delphi)**
  - **Crosscutting activities**

2

Exhaust Gas Sensor Development

- **Cooperative R&D Agreement (CRADA) with Low Emission Partnership (LEP) under USCAR**
- **Cost shared cooperative sensor R&D**
- **DOE lab participants:**
  - **Los Alamos National Laboratory**
  - **Sandia National Laboratory**
  - **Lawrence Livermore National Laboratory**
  - **Argonne National Laboratory**
- **OEMs perform test and evaluation of sensors developed at the labs**
- **Two labs will continue through FY 2001**

Sandia National Lab

- **SIDI stratified charge experiments**
  - $425K, Ongoing
- **Objective**: Better understanding of SIDI stratified charge combustion; optimization of combustion stability, emissions, fuel economy
- **Approach**: Experimentation using an optically accessible engine (color video, LII, LIF,
  - Observe: spray motion, wall wetting, vapor distribution, flame propagation; measure:HC, soot, NOx
  - Kiva modeling and 1-d simulations
- **Outcome**: Quantitative observations of in-cylinder processes; emphasis on measurements that can be generalized to other engine geometries

Oak Ridge National Lab

- **Study of injector and combustion chamber deposit formation in SIDI engines ($300k)**
- **Goal**: Define and quantify mechanisms and chemistry of deposit accumulation and adhesion
- **Approach**: Experiments and measurements using Mitsubishi GDI
  - Adhesion
  - Chemical composition, physical structure
  - Injection variables
  - Fuel composition, additive effects
- **Outcome**: Reduction in deposit buildup through fuels, coatings; operating conditions, other effects

Computer Modeling to Support GDI Engine Research (LANL)

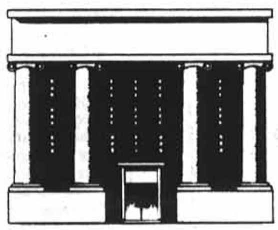
- **Provide 3-D CFD modeling support to research and production GDI engines being tested at Sandia National Laboratories - Livermore.**
  - **Interpret experimental data**
  - **Understand fuel/air mixture preparation**
  - **Improve computer submodels**
- **Extend and apply KIVA-3V to perform full-engine-cycle simulations. Use next-generation code CHAD when full-cycle-simulation capability available in CHAD.**
- **Provide extended models to LEP/USCAR members.**

Delphi Energy and Engine Management

- **SIDI injection and fuel system development satisfying ULEV**
- **Goal**: Develop a non-impingement SIDI injection and low pressure fuel system
  - $4.6M, 30 months 50% cost shared
- **Approach**: Jet stratified late injection, unthrottled operation,
  - Single fuel pump, low pressure/low cost fuel system, high efficiency atomizer
  - CFD, motoring optical engine tests, firing single-cylinder engine tests, multi-cylinder tests
- **Risks**: Injector fouling, good spray formation at low pressure, optimizing: geometry, injection, ignition, EGR
- **Outcome**: A lower cost SIDI injection and fuel system

SIDI University Grants

- **SIDI mixture formation, emissions sources, and fuel composition effects**
  - **Ron Matthews and Matt Hall**
    University of Texas, Austin
- **Direct-injection, spark-ignition engine combustion**
  - **Dom Santavicca,**
    Penn State University
- **Mixture preparation and nitric oxide formation in a GDI engine studied by combined laser diagnostics and numerical modeling**
  - **Volker Sick and Dennis Assanis, University of Michigan**
- **Hydrocarbon formation mechanisms in DI engines**
  - **Jaal B. Ghandi**
    University of Wisconsin - Madison



Grants are for approximately $100,000 per year for three years

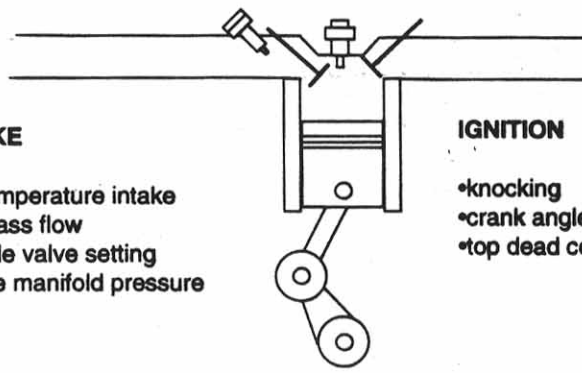
Crosscutting Activities

- **PM Comparative Toxicity** - National Renewable Energy Laboratory, Lovelace Respiratory Research Institute (LRRI), Southwest Research Institute
- **Objectives**: Analyze the comparative toxicity of CI and SI PM
- **Approach**:
  - Collect PM from SI and CI vehicles: from Baltimore tunnel and dynamometer tests
  - "Blind" samples will be sent to LRRI for comparative toxicity testing
  - In vitro (cell culture), in vivo (animal), standard mutagenicity tests

FY 2000 SIDI Projects

Project	Lab/Contractor
Engine R&D	
SIDI side injection	SNL/CA
University comb. R&D	SNL/CA, Univ.
SIDI central injection	SNL/CA
PM diagnostic	SNL/CA
SIDI modeling	LANL
Injector deposit study	ORNL
Near frictionless coatings	ANL
Fuel spray studies	ANL
NOx Sensor development	LLNL
O2 Sensor development	LANL
PM toxicity study	LRRI/SWRI
NOx catalyst evaluation	CRC, MECA
Component development	
Non-impingement DI sys	Delphi E
Active flow control	Mich State
USCAR LEP CRADAs	
Advanced in-car sensing	ANL
Exhaust gas sensors	LANL
" "	LLNL
" "	SNL/NM
HQ Assessments	
Technical support	HQ
	QSS

Basic Sensors for Fuel Mixture and Engine Management for Port Fuel Injected SI Engines



EXHAUST

•Oxygen sensor

INTAKE

•air temperature intake
•air mass flow
•throttle valve setting
•intake manifold pressure

IGNITION

•knocking
•crank angle
•top dead center

Sensor Variables

- **Performance**
  - Accuracy
  - Sensitivity
  - Selectivity
  - Cross sensitivity
  - Poisoning
  - Response time
  - Power consumption, signal strength
- **Physical**
  - Size, weight
  - Env. Compatibility
- Cost
- Life

Future Sensor Requirements Needed to Achieve Reduced SI Emissions

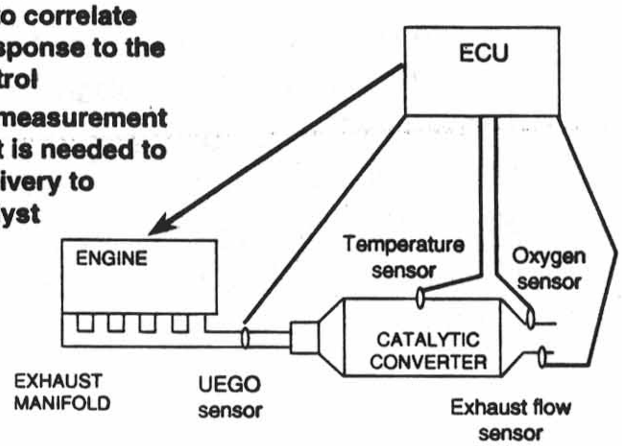
- **Control of Air/Fuel Mixture Requires:**
  - measurement of A/F ratio for each combustion event
  - fast response
  - misfire detection
  - Sensor types: O2, NOx, CO, HC, as well as exhaust flow and catalyst temperature
- **Ignition Timing Requires:**
  - Rapid pressure measurement during combustion will enable the following information to be gained:
    - crank angle position of peak pressure
    - knocking at cylinder of origin
- **Integration of these two sensors would enable cylinder-specific regulation**

Future Signal Processing and Control System Needs

- **Signal Processing Requirements**
  - Speed
  - Reduced sensitivity to measurement noise
  - Better use of information, predictive algorithms
  - **Recent algorithm improvements have enabled tighter control of A/F mixtures using existing oxygen sensors (SAE 980425)**
- **Control Systems Requirements**
  - Improved control/precision of fuel-air delivery
  - **HC emissions are reduced by fuel atomization to improve open loop combustion at cold start**

Exhaust Flow Sensors and Temperature Sensors are Being Studied to Augment the Oxygen Sensor Control

- **Exhaust flow measurement is necessary to correlate the sensor response to the feedback control**
- **Temperature measurement of the catalyst is needed to adjust A/F delivery to optimize catalyst performance**



SIDI Sensor Need: NOx

- SIDI engines operate in the lean-burn regime. As a result they require NOx adsorber-type aftertreatment. Adsorber technology may have the foremost need for a NOx sensor
  - Control of NOx adsorber regeneration requires NOx sensor
  - Control of NOx adsorber desulfurization may require SO_2 sensor

Sensor Need: Hydrocarbon and PM

- Monitoring HC is necessary for careful control during regeneration of absorber
- Higher PM emissions may require careful control of fuel delivery
- PM or HC sensors may also have application in closed-loop EGR control in SIDI (or CIDI) engines

Existing Sensor Types and Principles of Operation

- Electrochemical Solid State Sensors
  - NOx sensors
  - Oxygen sensors
- Piezoelectric Ceramic Sensors
  - Manifold air pressure
- Thermistor Sensors
  - Temperature

Future Trends and Sensors: SIDI Engines

- SIDI engines represent one promising path to improved fuel economy
- The SIDI engine will benefit from new sensor technology

Driving Towards Clean Air: Countdown to Zero

Tom Cackette

Deputy Director

California Air Resources Board

January 25, 2000

Outline

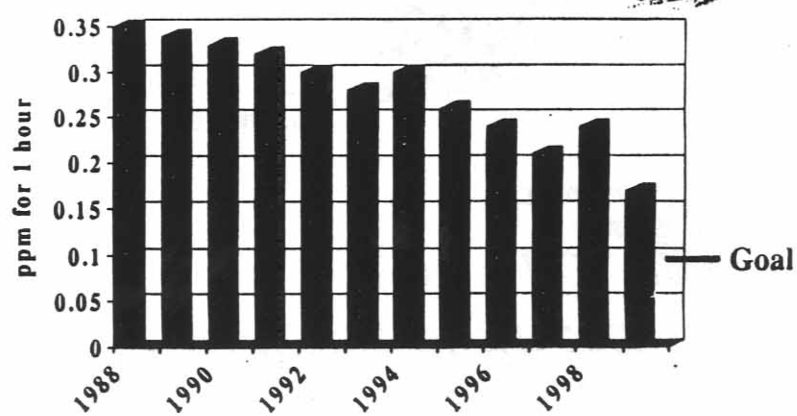
- Air pollution and health
- Sources of emissions
- Need for zero emission technologies
- Conclusions

Air Pollutants of Concern

Air Pollutant	Emission	Health Effect
Ozone	VOC, NO_x	Respiratory disease, irritation
PM_{10}, $PM_{2.5}$	PM, NO_x, SO_x	Respiratory disease, irritation, death
Toxics	Diesel PM, VOC	Cancer

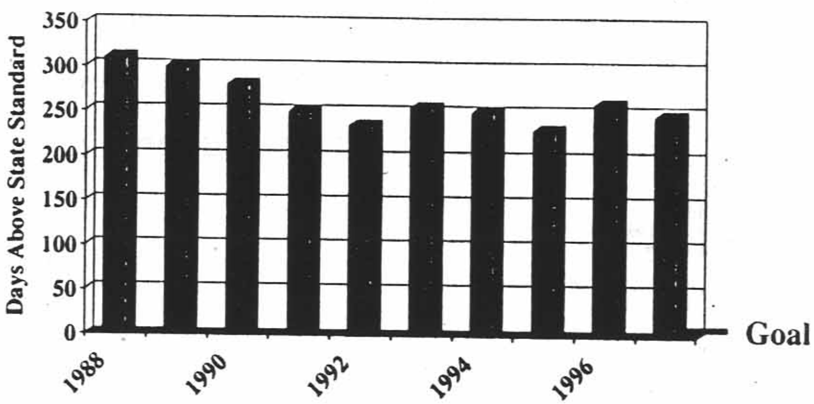
Air Quality Is Improving:

Highest Ozone: Greater Los Angeles



Less Progress with PM_{10}

Greater Los Angeles

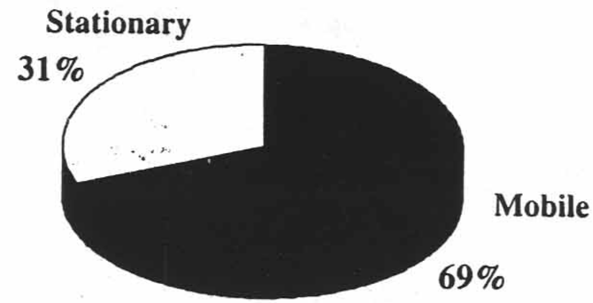


Based on 1 in 6 day monitoring

Sources of Emissions

VOC + NOx: 1990

Greater Los Angeles



Emission Reductions Needed for Ozone Attainment*

South Coast Air Basin

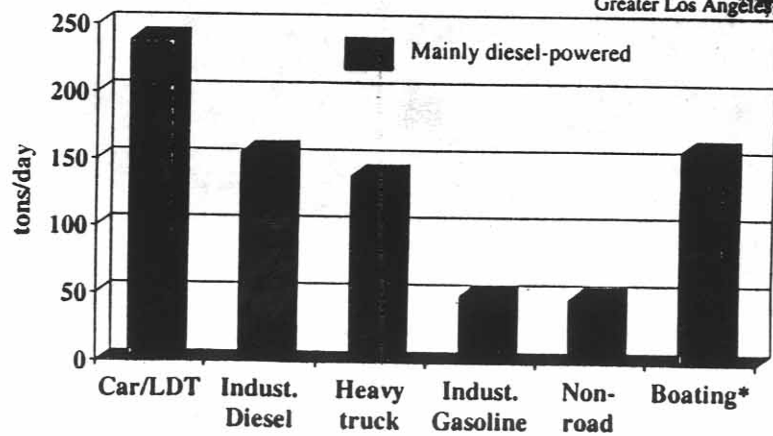
ROG	79%
NOx	59%

* By 2010, compared to 1990 baseline

Major Sources of Emissions

ROG + NOx: 2010

Greater Los Angeles

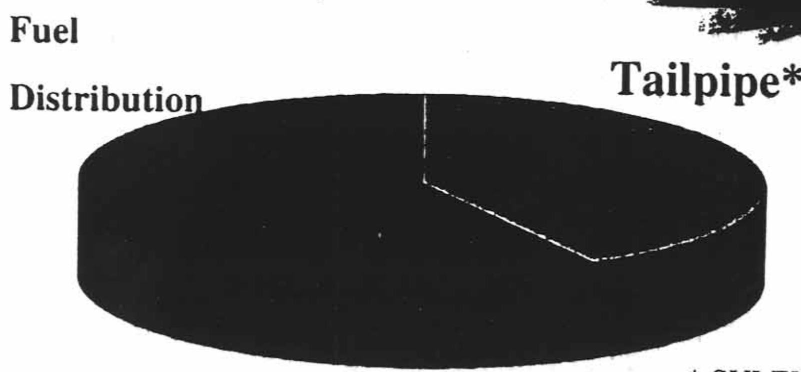


* summer weekend day

The Path to Clean Air

- Zero and near-zero emissions, e.g.
  - Cars
  - Urban trucks
  - Consumer products & solvents
  - Stationary power/heat sources
- Best control technology elsewhere

*Fuel Distribution Emissions vs. Cleanest Gasoline Car**



* SULEV

Counting Down to Zero Cars and Light Trucks

- Gasoline engines
  - Near-zero vehicle emissions possible (99+% ↓)
    - 2000 Nissan Sentra
    - 2000 Honda Accord EX
  - Emissions remain from fuel distribution
    - Terminals
    - Cargo tankers
    - Service stations

Count Down to Zero Cars and Light Trucks

- Battery electric vehicles
  - >1000 on-road in California
  - No vehicle emissions - ever!
  - Minimal recharging emissions (in CA)
  - Better efficiency (lower CO_2)
  - Lower operating cost
  - Limited range ~70 miles
  - High battery cost

Count Down to Zero
Cars and Light Trucks

- Hybrid electric vehicles
  - No range limitations
  - SULEV emissions feasible
- With 'no all electric range'
  - 2000 Honda Insight, Toyota Prius
  - Big 3: Diesel hybrids - *"emissions disadvantaged"*
  - No urban emission advantages
  - Better efficiency (lower CO_2)
- With 'electric range'
  - Emission advantages of battery EV

California Fuel Cell Partnership

- D/C, Ford, VW, Honda, Shell, Arco, Texaco, Ballard, CARB/CEC, DoE
- Prepare the market for fuel cell vehicles
  - Product recognition
  - Fuel infrastructure preparation
  - Supporting policies
- Vehicles on the road
  - Cars in 2000
  - Buses in 2001

Count Down to Zero
Cars and Light Trucks

- Fuel cell electric vehicles
  - Daimler/Chrysler NECAR, Ford P2000
  - Prototypes in 2000; commercial in 2004?
  - 'New' fuel likely needed
  - Zero or near-zero emissions
  - Better efficiency (low CO_2)
  - Cost reduction needed

Countdown to Zero
Heavy-Duty Trucks & Buses

- Diesel engines
  - Current engines
    - Low NOx and 'smoke free'
    - Fuel economy improved
  - Catalysts needed to further reduce emissions
    - Technology emerging quickly
    - Low sulfur fuel essential (~15 ppm) - Nationwide
  - Near-zero emissions feasible (98% reduction)
    - 0.2 g NOx, 0.01 g PM (/hp-hr)

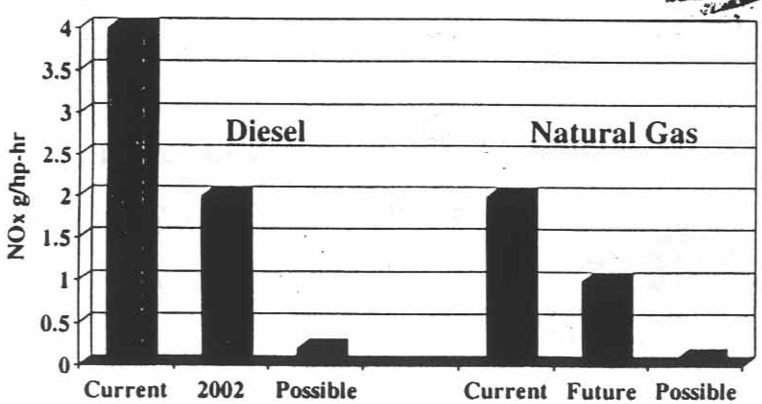
Countdown to Zero
Heavy-Duty Trucks & Buses

- Natural gas engines
  - Current engines
    - 50% fewer emissions than diesel (now)
    - CNG for transit buses
    - LNG for longer distance trucks
    - 'Corridor' refueling developing
  - Future engines
    - Cleaner than diesel (engine-out)
    - Catalysts/traps to keep ahead of diesel??

Countdown to Zero
Heavy-Duty Trucks & Buses

- Fuel cell engines
  - Transit buses
    - Hydrogen fueled
    - Zero emissions
    - Fuel efficiency better than diesel
    - Proposed ARB regulation
      - 15 bus roll-out by 2004
      - 15% purchase requirement 2008+
    - Challenge: Cost reduction
  - Other applications
    - Line haul trucks, locomotives

Countdown to Zero
NOx Emissions - Comparison



Best Technologies and Fuels
Other Applications

- Car technology - Gasoline
  - Transfer to industrial equipment, boats
- Truck/bus technology - Diesel
  - Transfer to construction/farm equipment
  - Lower sulfur off-road diesel fuel

Conclusions

- Today's LEVs still too dirty
- Zero & near-zero technologies needed
  - Battery EVs
  - Fuel cells
  - Combustion engines e.g. SULEV
- Cleanest fuels are enablers
  - 95+% after-treatment efficiency
  - New fuels for fuel cells
- Technology will get us clean, healthy air

INTERNATIONAL FUEL CELLS

State of Development of PEM Fuel Cells

Presented to:

The DOE Sensors for Fuel Cells and CIDI/SIDI Engines Workshop

By:

Douglas Wheeler
January 25, 2000

International Fuel Cells
A United Technologies Company

Overview

- PEM Fuel Cell for Transportation Applications
- PEM Fuel Cell for Stationary Power Generation
- PEM Fuel Cell for Portable Power Applications

International Fuel Cells
A United Technologies Company

Overview

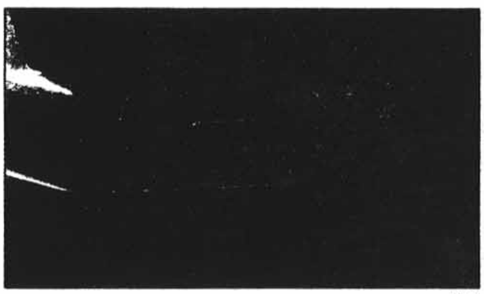
PEM Fuel Cell for Transportation Applications

- Replace ICE Power Source and APU
- Primary Characteristics for Both Applications
  - High Efficiency
  - Low Level Pollution: Near Zero Emissions
  - Range compatible with gasoline fueled ICE
  - Potential for Multiple Fuel Applications: gasoline, methanol, hydrogen

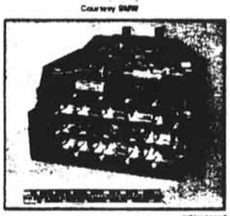
International Fuel Cells
A United Technologies Company

Transportation Development Programs

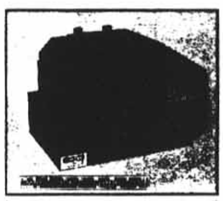
APU Program - BMW



Courtesy BMW



- 5 kW H_2 - Air
- Power Plant
- Auxiliary Power Unit (APU)
- 7 Series Vehicle



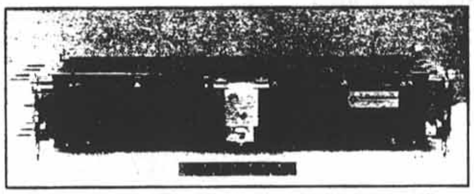
International Fuel Cells
A United Technologies Company

Ballard NECAR

Source: 1996 TOKYO AUTO SHOW

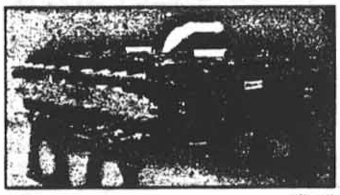
International Fuel Cells
A United Technologies Company

Current IFC PEM Cell Stacks



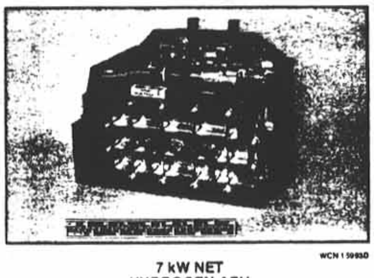
WCN 15089

45kW
HYDROGEN DESIGN



WCN 16166

70 kW
GASOLINE REFORMATE DESIGN



WCN 15993D

7 kW NET
HYDROGEN APU

International Fuel Cells
A United Technologies Company

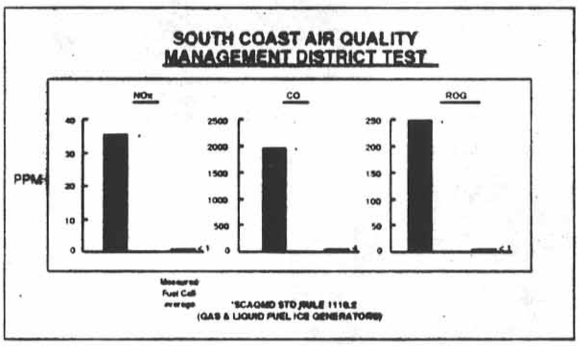
Overview

PEM Fuel Cell for Stationary Power Generation

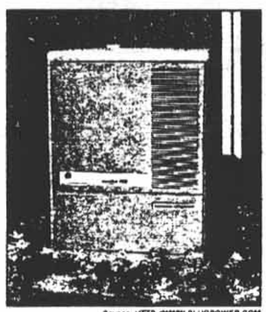
- Residential Applications: 5kW to 15 kW
- Commercial Applications: 50 kW to 1MW
- Primary Characteristics
  - High Reliability, High Efficiency, Ultra-Low Emissions, Multi-Fuel Capability

International Fuel Cells
A United Technologies Company

Stationary Power Plants



IFC



Source: HTTP://WWW.PLUGPOWER.COM

Plug Power

International Fuel Cells
A United Technologies Company

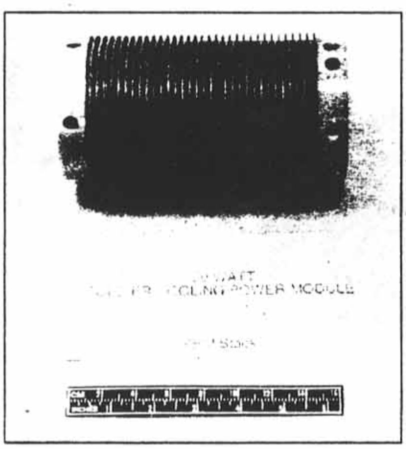
Overview

PEM Fuel Cell for Portable Power Applications

- Extended Life
- Rechargeable Fuel (Mechanically or Reversible)
- High Power Output
- Auxiliary Power
  - 5W to 1kW range

International Fuel Cells
A United Technologies Company

Soldier Cooling Power Module



International Fuel Cells
A United Technologies Company

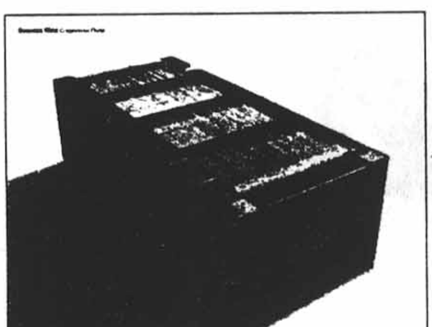
PEM Fuel Cell Types

Pressurized vs. Atmospheric PEM

- Water Removal Concepts
  - Pressurized Fuel Cells: Removal of Water through Evaporation
  - Pressurized Fuel Cells: Removal of Water through Entrainment
  - Atmospheric Pressure: Removal of Water into Coolant

International Fuel Cells

Pressurized Systems



Source: HTTP://WWW.BALLARD.COM

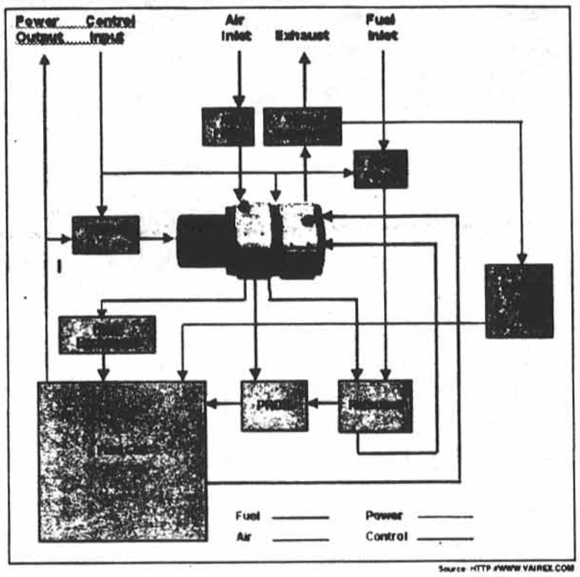
Ballard Stack

Source: HTTP://WWW.VAIREX.COM

Vairex Integrated Compressor/Expander

International Fuel Cells

Vairex System Concept

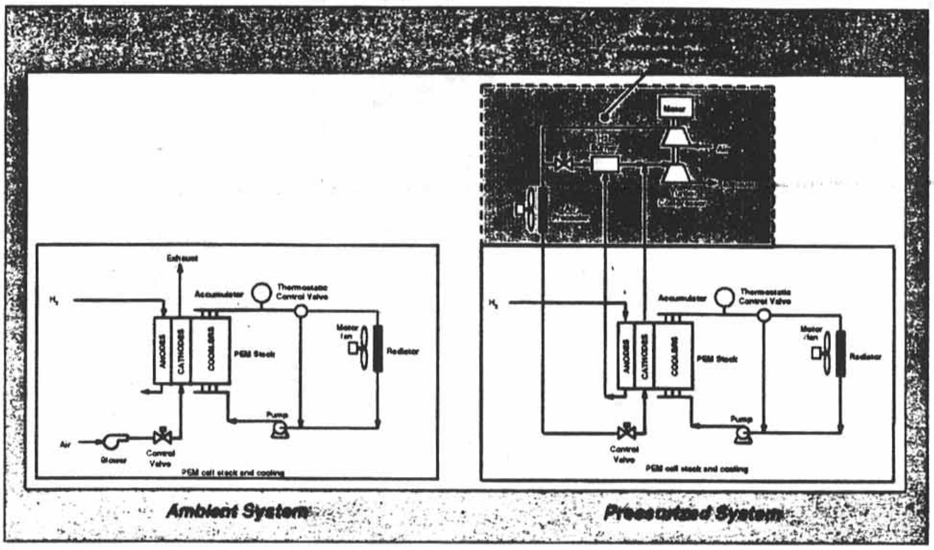


Source: HTTP //WWW.VAIREX.COM

Pressurized and Atmospheric Power Plants

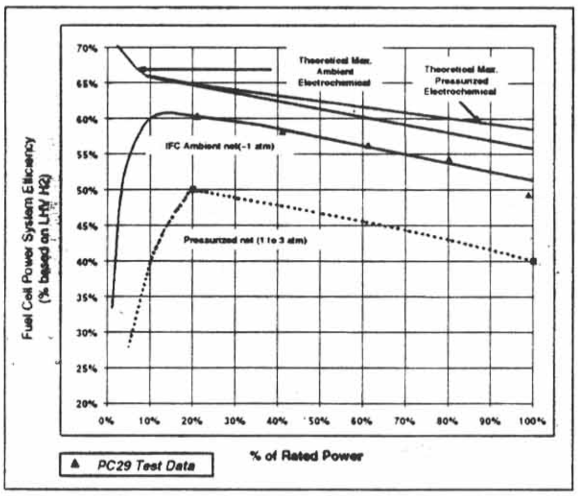
- Power Plant Efficiency
  - Choice of compressor
  - Efficiency Controls
- Peak Power Design
  - 50 kW Plant: Compressor for Peak Power
  - Partial Power
    - Compressor Efficiency Loss: Turn Down Issue

Ambient vs. Pressurized Systems



International Fuel Cells
A United Technologies Company

Efficiency: Ambient vs. Pressurized



Advantage of Ambient PEM Technology

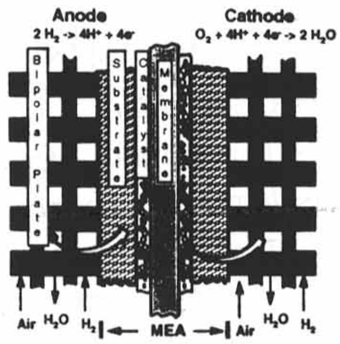
- Higher fuel mileage
- Lower complexity
- Lower weight
- Smaller
- Better transient response

Leads to lower cost and better performance

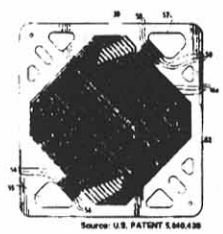
International Fuel Cells
A United Technologies Company

Cell Stack Assembly

- Major Components
  - Membrane
  - Electrode
  - BiPolar Plates
  - End Plates
- Design Issues
  - Pressurized
  - Atmospheric
  - Internal vs. External Manifolds
  - Seals



IFC



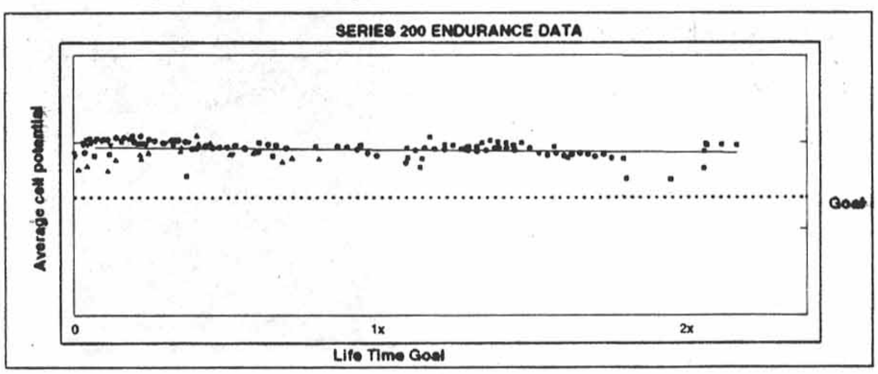
Ballard

International Fuel Cells

Cell Stack Assembly - IFC

Technical Issue

- Life Targets
  - 5,000 hrs. Transportation
  - 50,000 hrs. Stationary



International Fuel Cells

PEM Fuel Cells
Fuel Processing

- Fuel Processing Issues:
  - Hydrogen / Air
    - Technical Issue: Hydrogen Storage
  - Reformed Carbonaceous Fuel / Air
    - Technical Issue: Poisons
      - Carbon Monoxide, Sulfur, Ammonia
    - Direct Methanol / Air
      - Technical Issue: Anode Catalyst and transport of Methanol through membrane

International Fuel Cells
A United Technologies Company

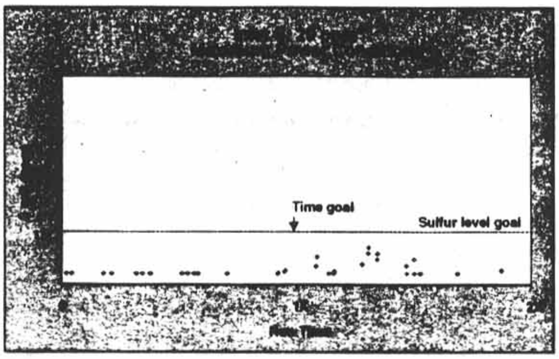
Fuel Processor Components

- Desulfurizer
- Fuel Reformer
  - ATR/POX
  - CSR
- Shift
  - Low Temperature
- PROX/Sox

International Fuel Cells
A United Technologies Company

Fuel Processor
Desulfurizer

- Technical Issues
  - Sulfur Free Fuel
  - <0.05 ppm S
- Stationary
  - Hydrodesulfurizer
  - Commercial
- Transportation
  - Technology Breakthrough Needed



*California Reformulated Phase II Gasoline

International Fuel Cells

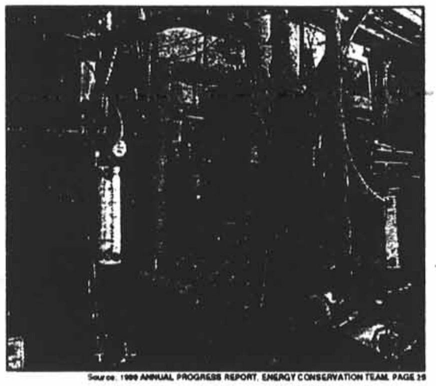
Fuel Processor
Shift

- Advanced Catalyst
  - Today: Cu/Zn - Over 2 million commercial hours in fuel cell applications
  - Future: Precious Metal Catalyst (ANL)
- Technical Issue
  - Size and volume of Cu/Zn based shift
  - High carbon monoxide
    - 1% CO
  - Thermal Balance
    - Heat Exchangers

International Fuel Cells

Fuel Processor
Reformer

- ATR/POX
  - Transportation & Stationary
    - Rapid Start-Up
    - High Carbon Monoxide
    - Ammonia Formation
- CSR
  - Stationary & Fleet
    - Slow Start-Up
    - Weight / Volume / Cost



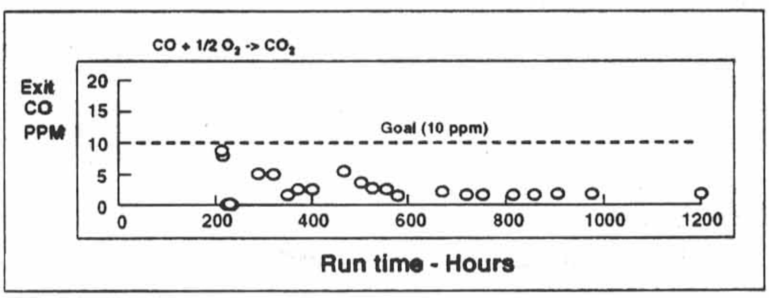
Source: 1999 ANNUAL PROGRESS REPORT, ENERGY CONSERVATION TEAM, PAGE 29

EPYX Model B

International Fuel Cells
A United Technologies Company

Fuel Processor
PROX/SOX

- Technical Issues
  - Transient Response
  - Residual CO
    - Need <10 ppm
  - Ammonia
  - Catalyst Stability



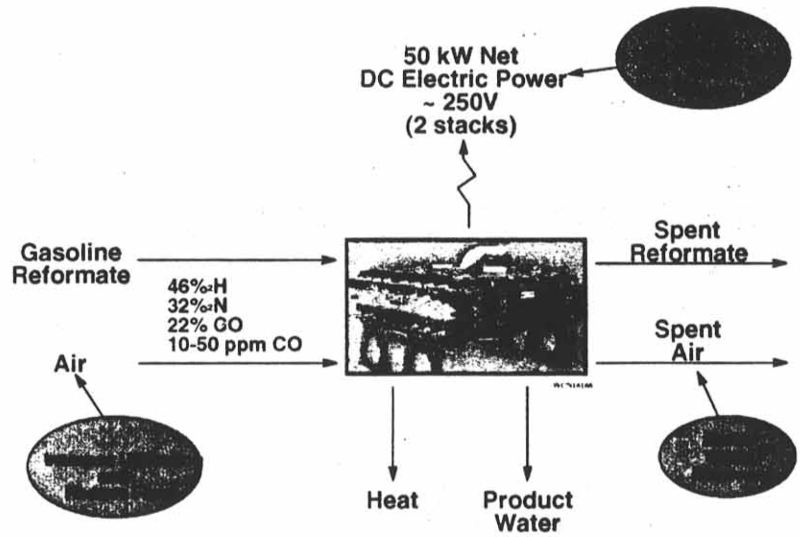
International Fuel Cells

Conclusions/Status

- PEM Power Plants
  - Subsystems Approach Performance Levels for Transportation
  - Subsystems Approach Performance Levels for Stationary
  - Component Technology Issues:
    - Cost
    - Power Density
    - Durability

International Fuel Cells
A United Technologies Company

Technology Status
Series 300 Cell Stack Technology Program



International Fuel Cells
A United Technologies Company

State Of Development – CIDI Engines

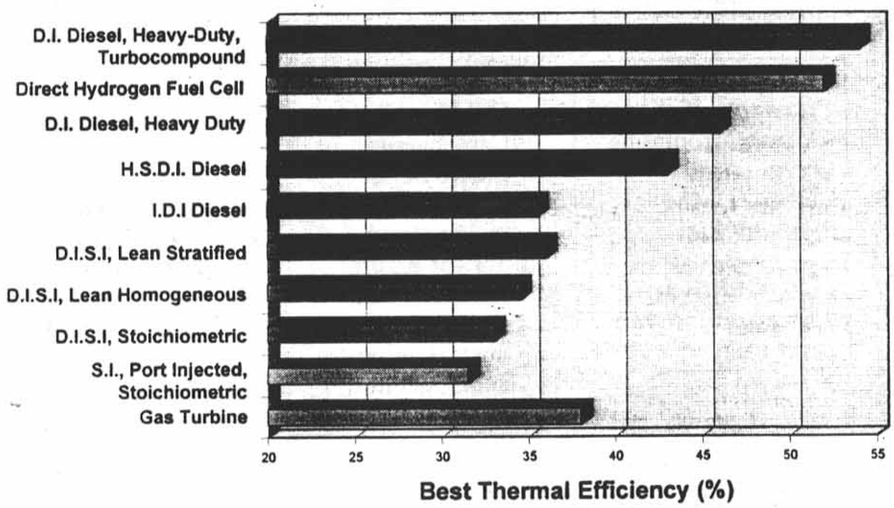
DOE Sensors Workshop

January 25-26, 2000

Rich Belaire

Ford Motor Company

Why Are We Interested In CIDI Engines ?



Emerging HSDI Engine Features

Engine Feature	"Current" CIDI	Emerging CIDI	Advantage Over Current: NOx Emiss.	PM Emiss.	NVH	Power Density	Fuel Econ
Combustion System	Two Valve	Four Valve	●	●		●	●
Fuel Injection System	Rotary Pump	Common Rail	●	●	●	●	●
Aftertreatment	Oxidation Catalyst	Lean NOx Catalyst	●				
Boosting System	Fix-Geometry Turbocharger	Variable Geometry Turbo	●	●		●	●
Actuators	Pneumatic	Electric	●	●			
Base Structure	Cast Iron & Alum.	Aluminum				●	

Sensors1

Ford

DOE Sensors Workshop

Pre-Combustion → In-Cylinder Combustion → Post-Combustion

Fuel Reformulation
- Lower Sulfur
- Lower Aromatics

Oxygenates
- DME, DMM
- w/conv fuel

Fuel Additives
- Cetane Improvers

Dual Fuel

Design Parameters
- Cyl Head Layout
- Cam Events
- Intake Ports
- Compression ratio
- Piston Bowl

Fuel Inj Equip
- Common Rail
- Unit Injectors
- Rate Shaping
- Split Injection
- Piezo Systems

NOx Control
- Lean NOx Cats
- Non-Thermal Plasma

PM Control
- Oxy Catalysts
- PM Filters
- Thermal Oxidation
- Non-Thermal Plasma

NVH Refinement

----------------- **Strategy** -----------------

Turbocharging **EGR** **Sensors**

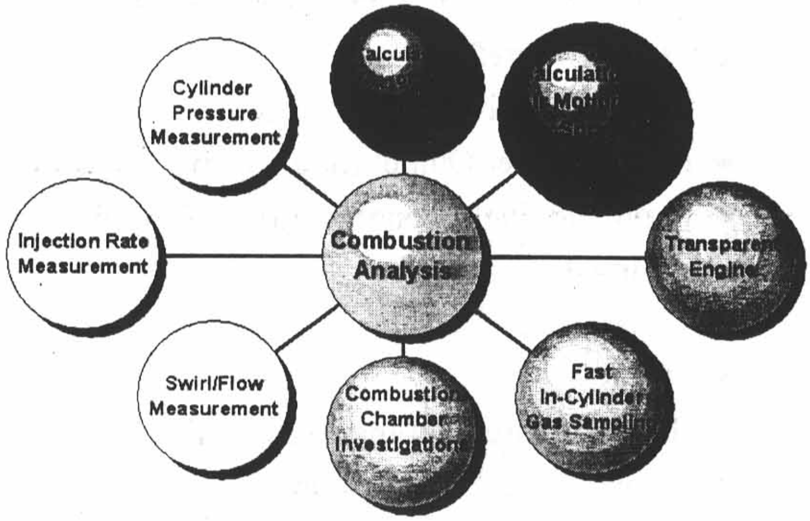
Sensors1

Ford

Ref: SAE 981914

DOE Sensors Workshop

Tools Employed To Improve In-Cylinder Performance



Sensors1

From FEV

DOE Sensors Workshop

Light-Duty Diesel vs. Light-Duty Gasoline Vehicles

Environmental Benefits

- Up to 35% increase in fuel economy
- Greater than 15% decrease in CO_2 emissions
- Greater than 20% decrease in GHG emissions
- Very low CO and HC emissions

Environmental Concerns

- Order of magnitude greater PM emissions
- 2X increase in NO_X emissions

Sensors1

DOE Sensors Workshop

Trend Towards Higher-Speed Diesel Engines

Customer Benefits

- Improved Driveability
- Higher Power Output for a Given Peak BMEP
- Improved Fuel Economy, Lower Emissions

Enabling Technologies

- 4-Valves Per Cylinder
- Direct Injection
- High Pressure Fuel Injection Equipment
- Turbocharging, Intercooling
- Light Weight Materials, Balance Mechanisms

Example 1 : V8 BMW Diesel

Features :

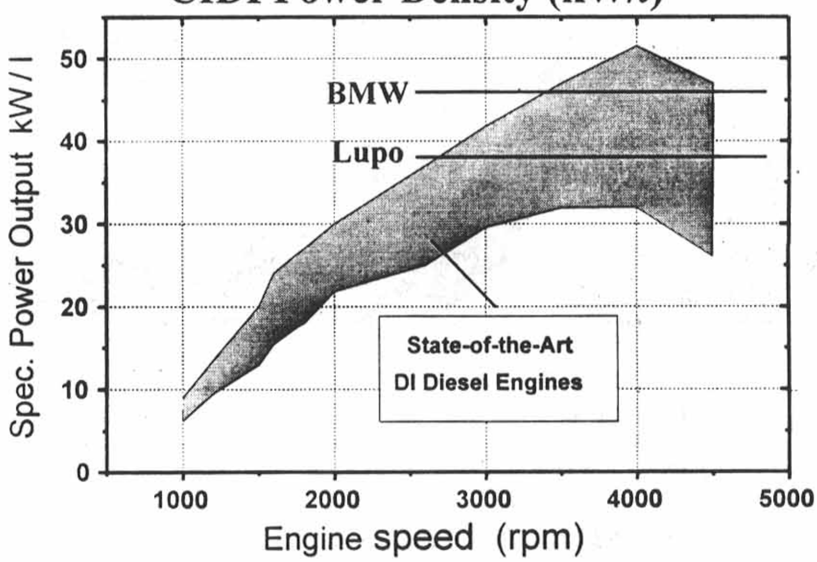
- 3.9 L Displacement
- 180 kW (245 bhp) @ 4000 RPM
- 560 Nm (413 ft-lb) @ 1800 RPM
- 4-Valves/cylinder, DOHC layout
- DI, High-pressure (1350 bar), dual common rail
- Dual VNT turbochargers, electronic control
- Dual air/air intercoolers
- Controlled, cooled EGR
- Iron block incorporating vermicular graphite

Example 2 : I3 VW Lupo Diesel

Features :

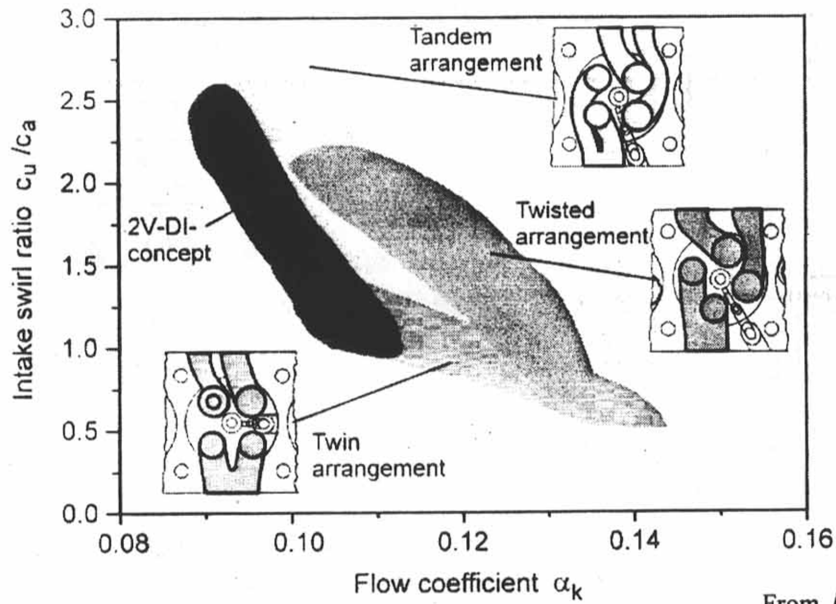
- 1.2 L Displacement
- 45 kW (61 bhp) @ 4000 RPM
- 140 Nm (103 ft-lb) @ 1800 RPM
- 2-Valves/cylinder, SOHC roller-rocker layout
- Single VNT turbocharger
- Cam-actuated DI unit injectors w/electronic control
- Single air/air intercooler
- Cooled EGR
- Aluminum cylinder head and block

CIDI Power Density (kW/ℓ)



4-Valves Per Cylinder Architecture

- Allows Central Injector Location
  - ➔ Promotes Symmetric Fuel Distribution
- Higher Volumetric Efficiency
  - ➔ Supports High Excess Air Needs of Diesel
- More Flexibility in Trade-off Between Swirl and Airflow
  - ➔ Combustion System Optimization For Fuel, Emissions
- Reduces Valvetrain Mass
  - ➔ Possible NVH and Valvetrain Stability Improvements

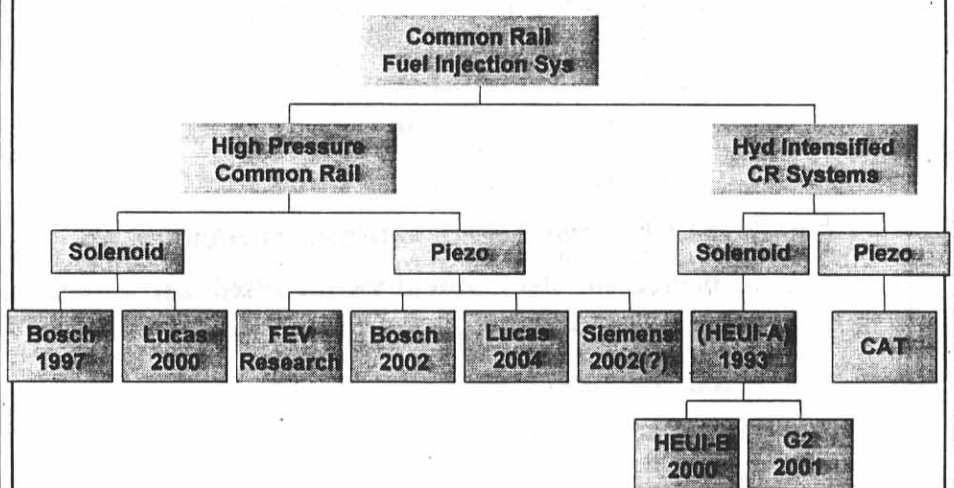


From FEV

High Pressure Fuel Injection Equipment

- High Injection Pressure at Low Engine Speed
  - ➔ Small Fuel Quantities w/Excellent Atomization
- Higher Fuel Delivery Rates at Higher Engine Speed
  - ➔ Fuel-Derived Energy To Promote Diffusion Burning
- PM and NOx Emissions Control
  - ➔ Injection Rate Shaping Matched To Engine Speed/Load
- NVH Management
  - ➔ Rate Shaping To Control Rate Of Pressure Rise
- Can Support V6 and V8 Designs
  - ➔ Hardware and Software Speeds Increasing

Common Rail Fuel Injection Systems



Fuel Injection Equipment (FIE)

Desirable Characteristics :

- High pressure over engine speed range
- Electronic control of pilot injection
  - Timing
  - Quantity of fuel injected
- Adjustable opening rate to control NO_X emissions
- Fast closing rate to minimize PM emissions
- Electronic control of multiple injection pulses
  - Combustion rate shaping
  - Providing exhaust HC for lean NO_X catalyst action
  - Split injections

High Pressure Fuel Injection Equipment

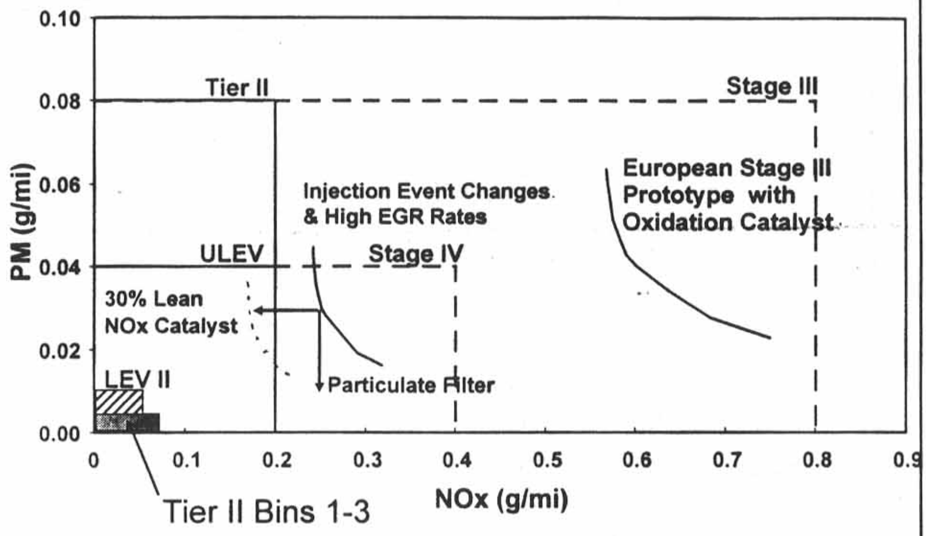
Achieving low engine-out emissions requires :

- Fuel injectors with small diameter holes
- High pressure at the nozzle tip

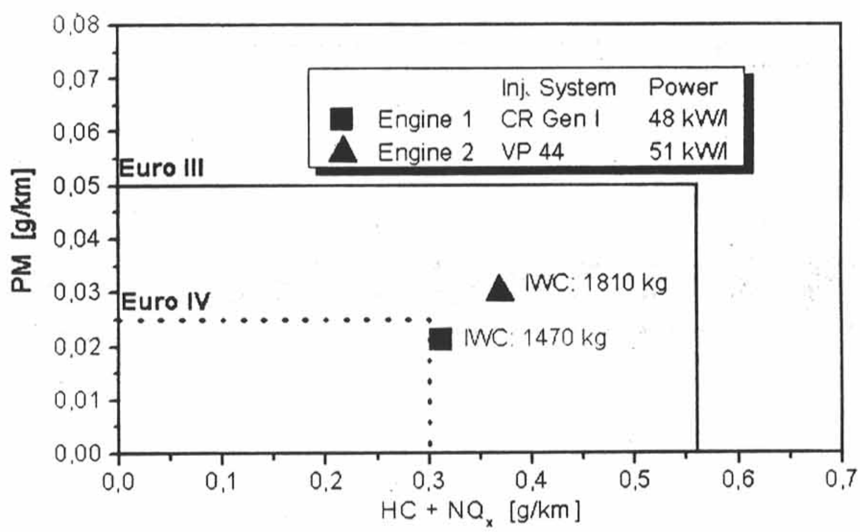
Current advanced FIE development focused on :

- Cam-driven, electronically controlled unit injectors
- High pressure common rail
- Intensifier fuel systems
- Piezoelectric actuated systems
- Injection rate control techniques
- Variable orifice nozzles

NOx - Particulate Trade-Off



Sensors1

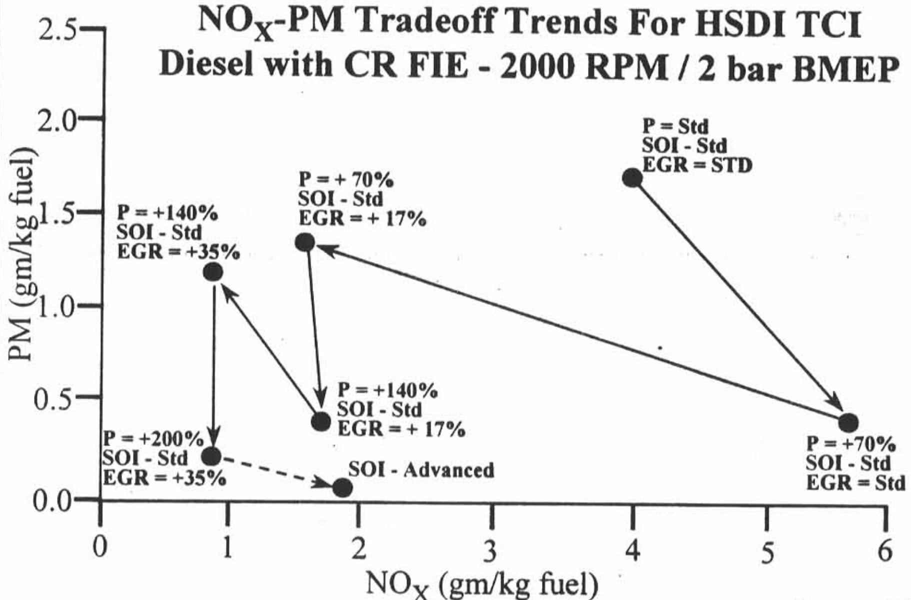


From FEV

Sensors1

DOE Sensors Workshop

NO_X-PM Tradeoff Trends For HSDI TCI Diesel with CR FIE - 2000 RPM / 2 bar BMEP



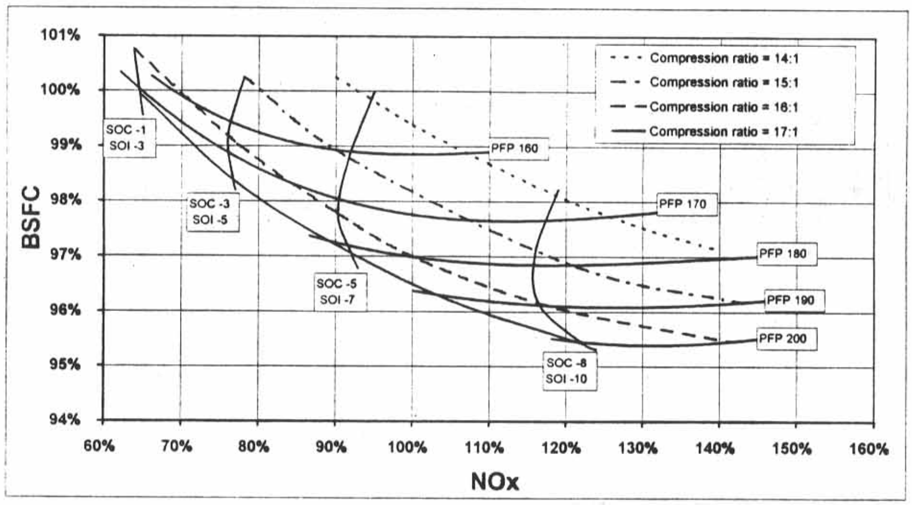
Sensors1

Source : AVL

Ford

DOE Sensors Workshop

Fuel Consumption Trade-Off

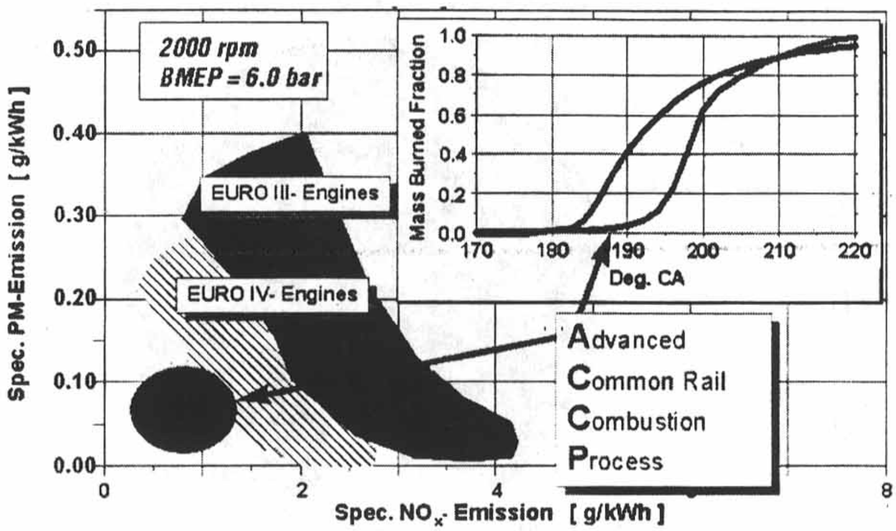


Sensors1

Source : AVL

Ford

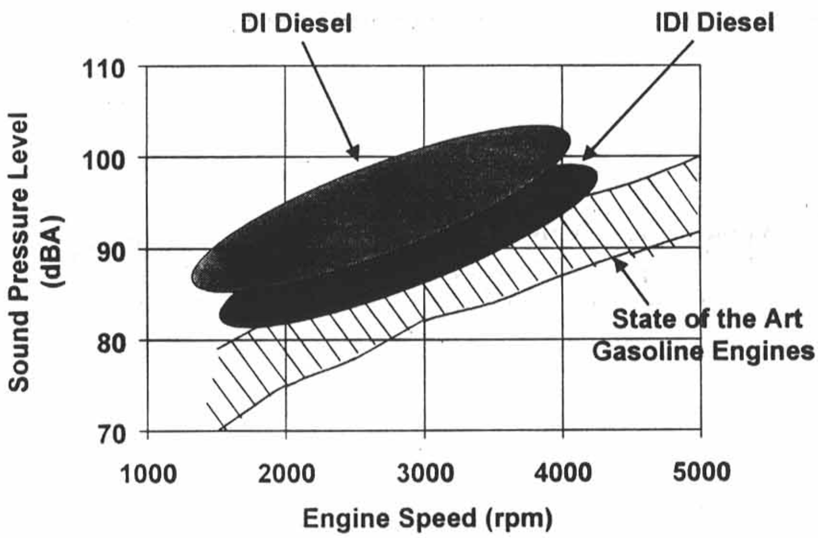
DOE Sensors Workshop



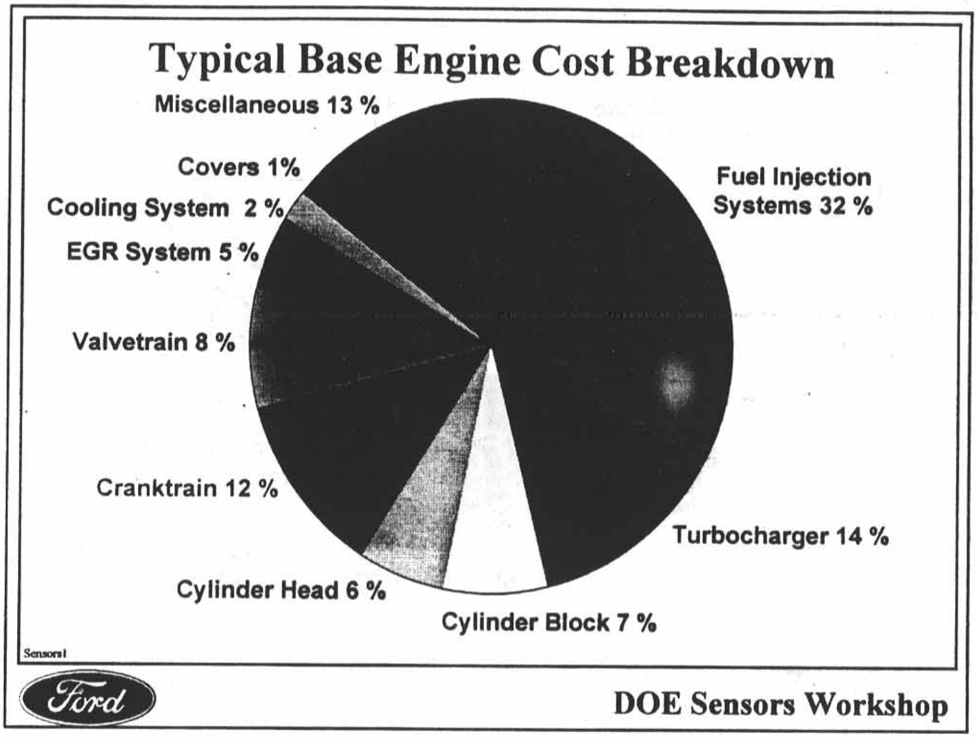
From FEV

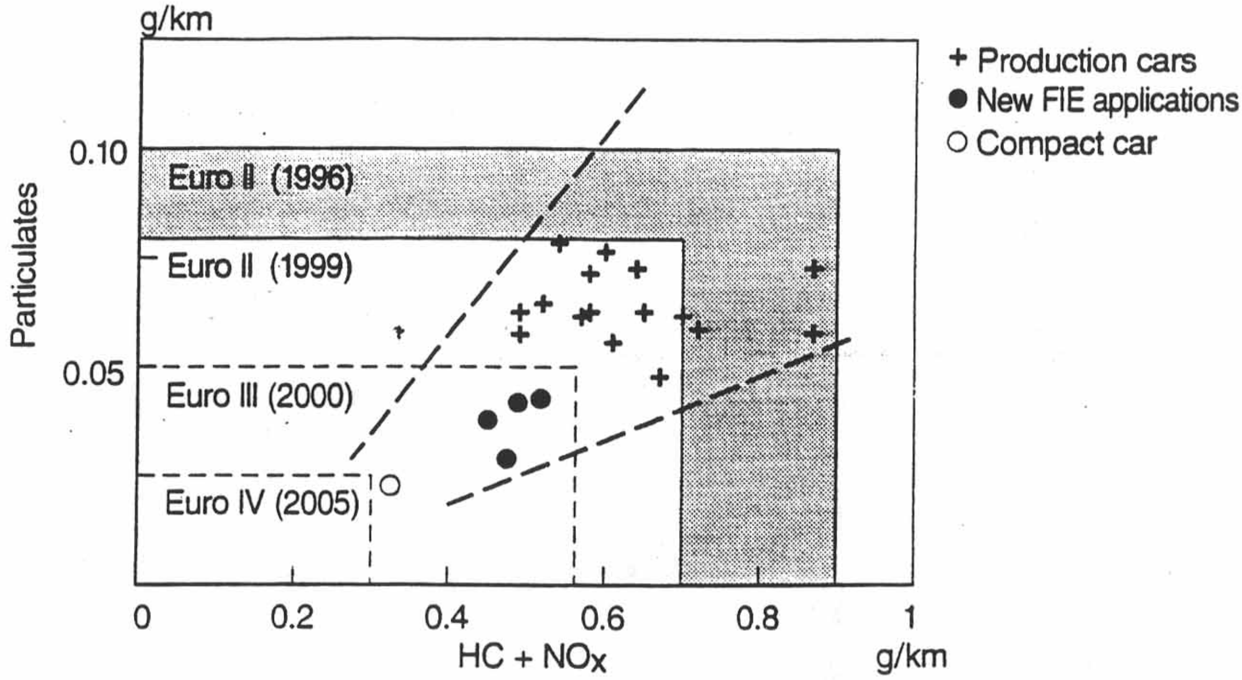
Sensors1

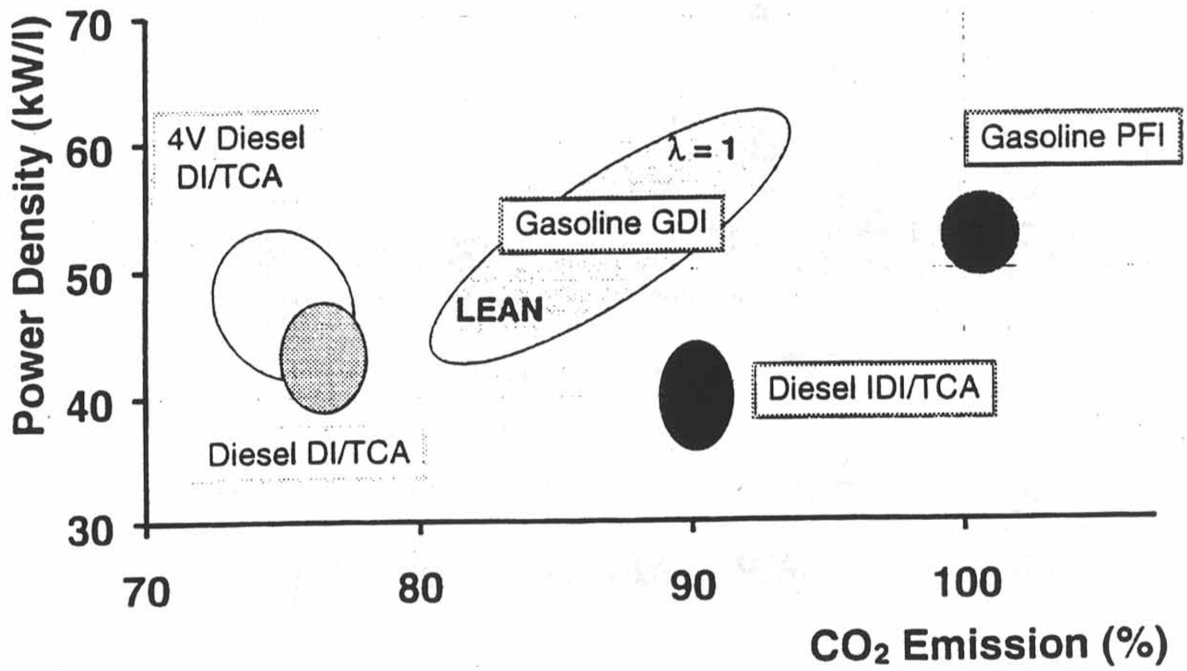
Broad NVH Comparisons



Sensors1

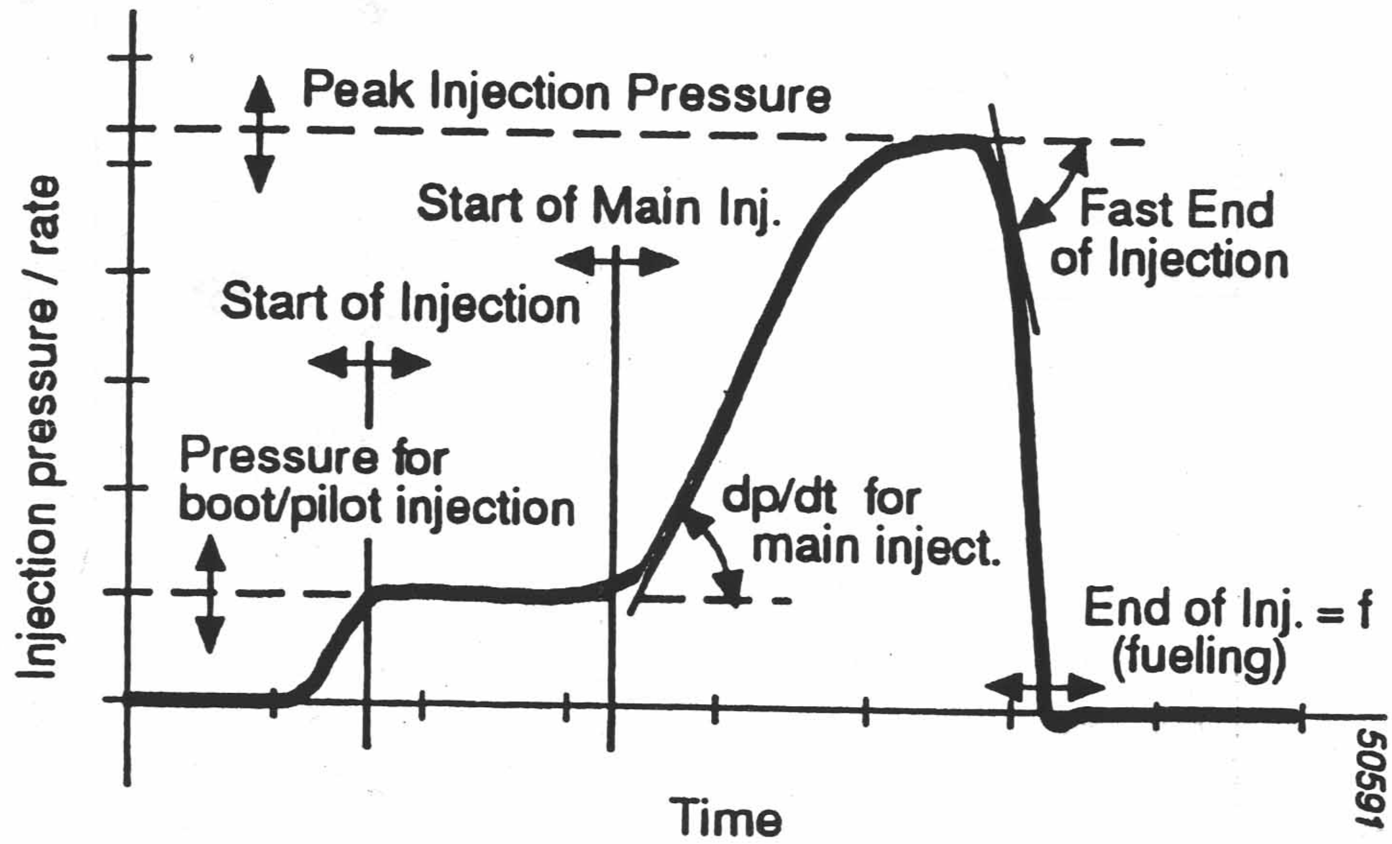

Typical Base Engine Cost Breakdown
Miscellaneous 13 %
Covers 1%
Cooling System 2 %
EGR System 5 %
Valvetrain 8 %
Cranktrain 12 %
Cylinder Head 6 %
Cylinder Block 7 %
Turbocharger 14 %
Fuel Injection Systems 32 %
Sensors1
Ford
DOE Sensors Workshop





REF: ENGINE & ENVIRONMENT CONF.
GRAZ AUSTRIA SEPT 1997

Injection Requirements for Fully Flexible Research FIE



SOURCE: AVL

SOURCE = AVL

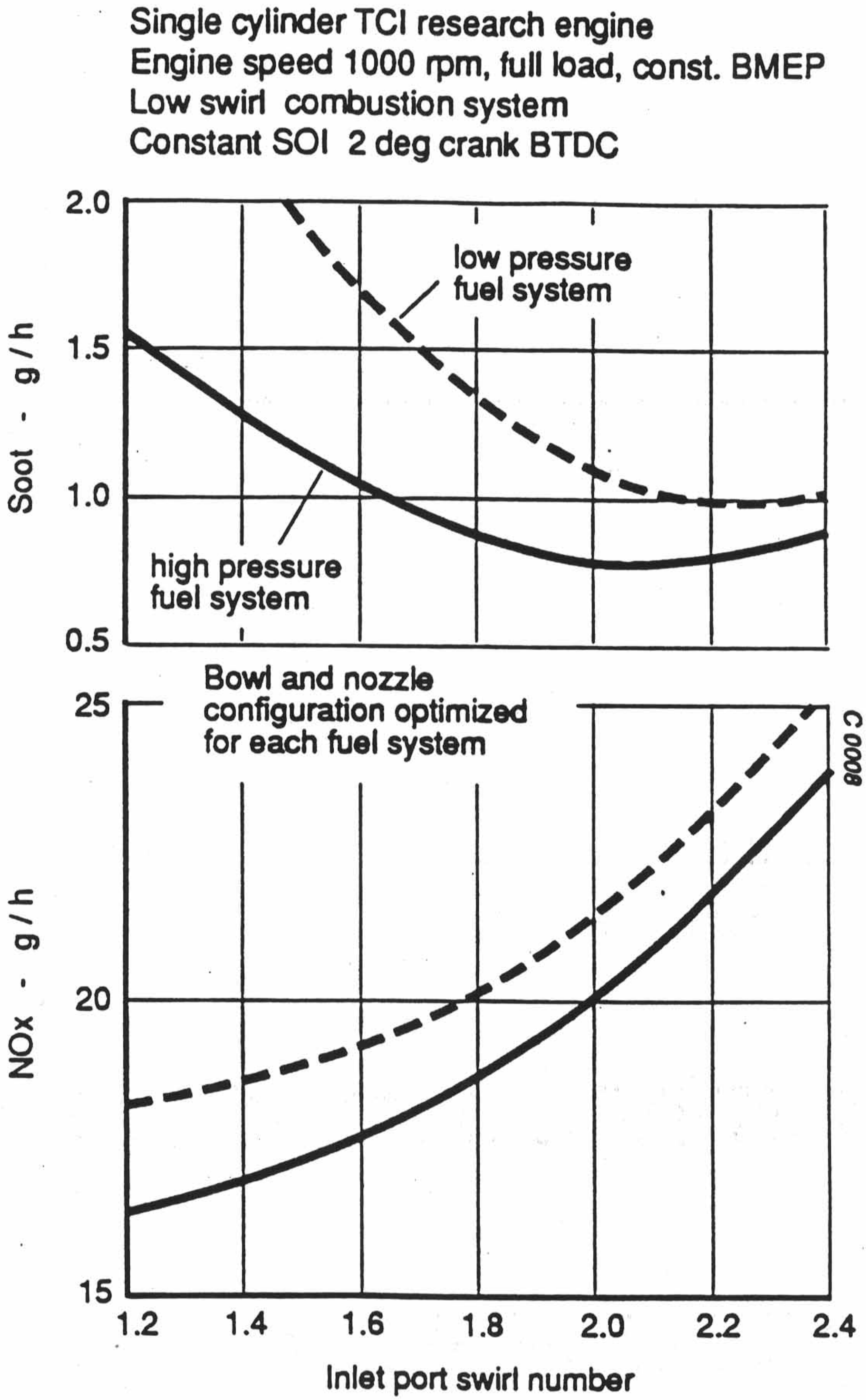


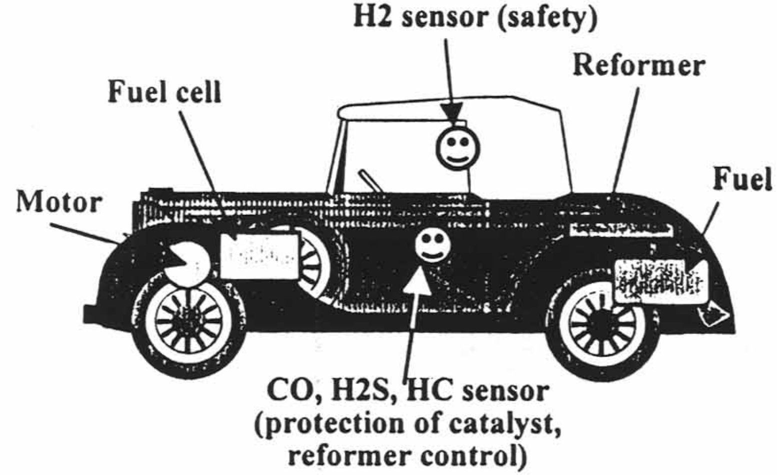
Figure 4: Effect of Charge Rotation on Soot and NOx-Emission

SENSORS; an Overview

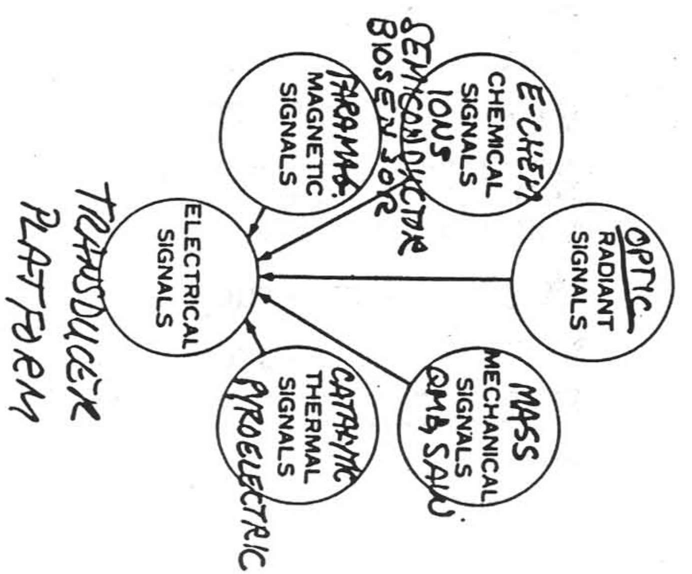
Joseph R. Stetter
Illinois Institute of Technology
Chicago, IL 60616

LLNL/DOE WORKSHOP
Sensors for Fuel Cells and CIDI/SIDI Engines
Jan. 25-26, 2000; Berkeley, CA.

Sensors in the Fuel Cell-Powered Vehicle



TRANSDUCER



SENSORS: Physical, Chemical. APPLICATIONS: Need? Approach?

- PHYSICAL - T, P, position, acceleration, mass,
- ***CHEMICAL*** - oxygen, flex fuel, cabin "odor,"
- CONTINUOUS vs POINT SOURCE.
- APPLICATIONS
  - PROCESS monitor and control.
  - HEALTH AND SAFETY.
  - ENVIRONMENTAL.

CHEMICAL SENSORS ARE NEEDED.

- Emissions - control [O_2, HC, NO_x]
- Emissions - monitor [HC, NO_x, CO, particle]
- Vapors - evaporative, fuel control.
- Human Comfort - odor, RH, T, …
- Function - oil quality, fuel quality, …
- Fuel Cell - poisons [H_2S, …], H_2, CO, O_2, HC
- Other - CO_2 …specific fuels, arrays, …SO_2, ...

The ANALYTICAL GOAL is to make a RELIABLE measurement!

- VALID ----> validity
- PRECISE ----> precision
- ACCURATE ----> accuracy

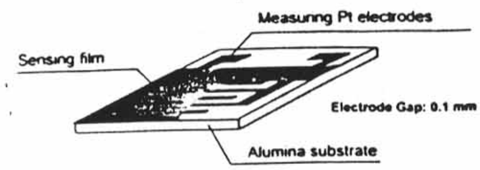
WHY AREN'T CURRENT SENSORS GOOD ENOUGH?

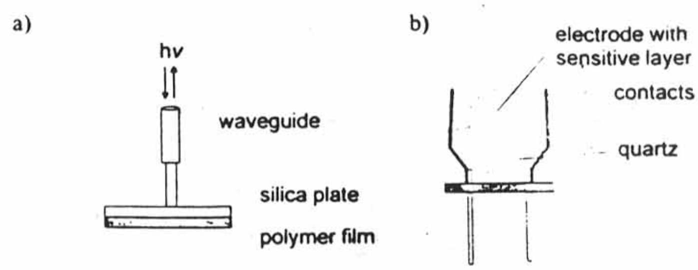
- RANGE
- ***TEMPERATURE***, PRESSURE, RH
- POWER, SIZE, SHAPE, ...
- ***RESPONSE TIME***
- ***SELECTIVITY***
- SENSITIVITY
- ***STABILITY***
- ***COST***

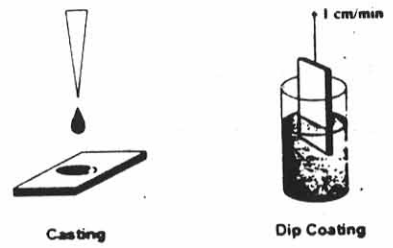
CHEMICAL SENSOR
-biosensor-

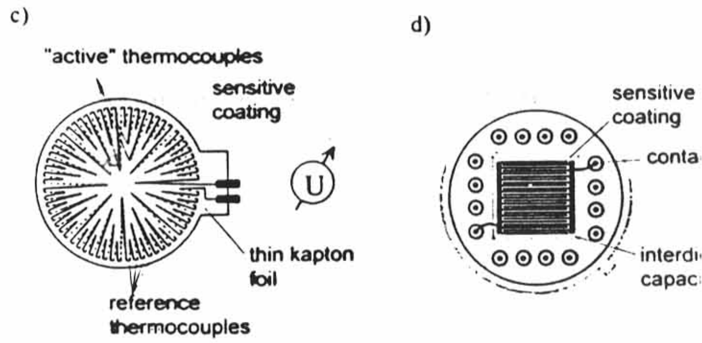
a small self-contained integrated system of parts that, as the result of a chemical interaction or process between the analyte and the device, transforms chemical or biochemical information of a quantitative or qualitative type into an analytically useful signal.

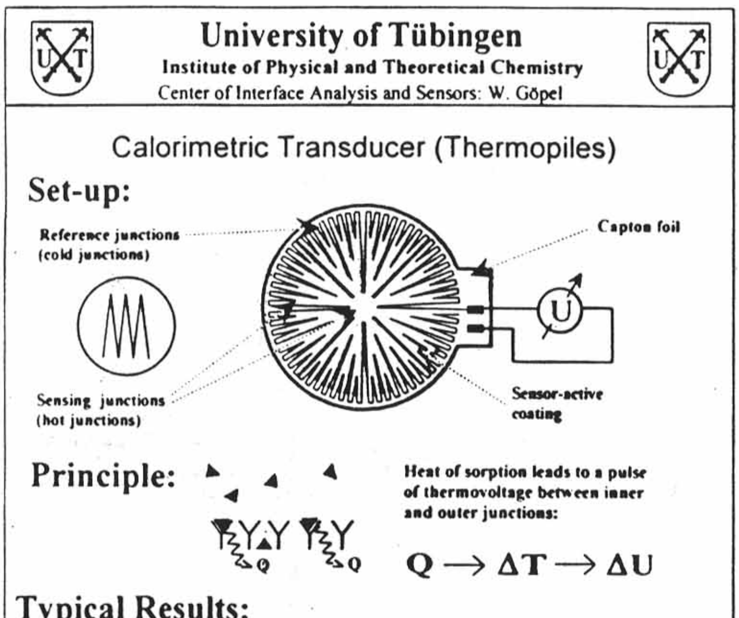
Sensor Substrate and Thin Film Preparations

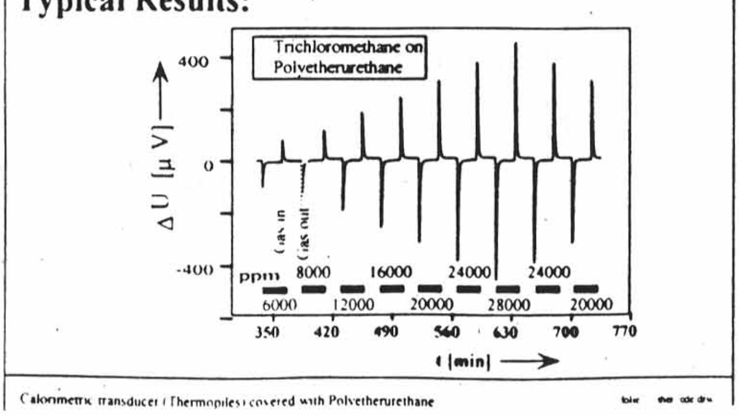


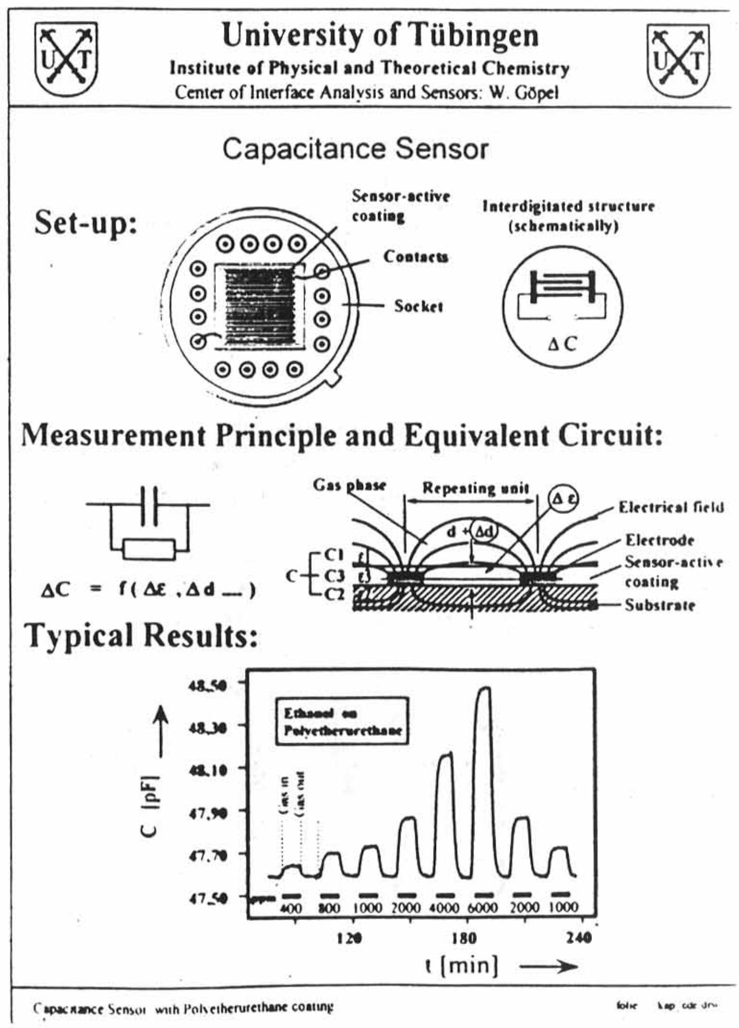






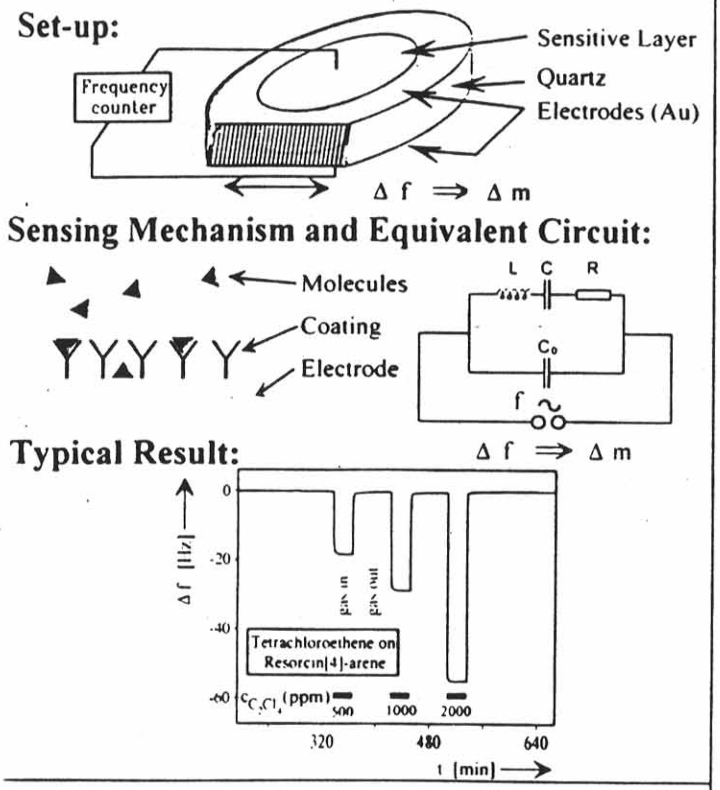






University of Tübingen
Institute of Physical and Theoretical Chemistry
Center of Interface Analysis and Sensors: W. Göpel

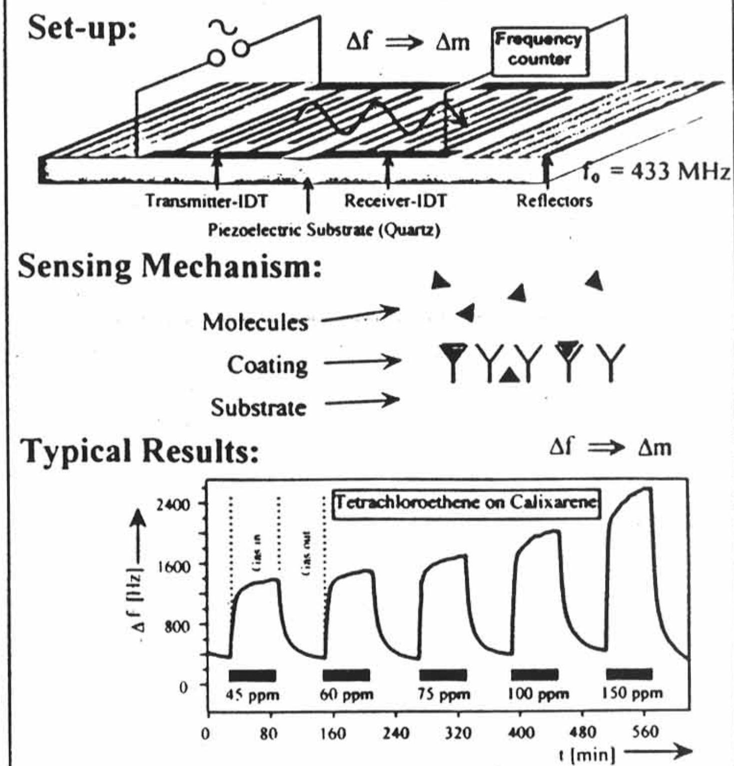
Sensor with Quartz Microbalance as Mass Sensitive Transducer



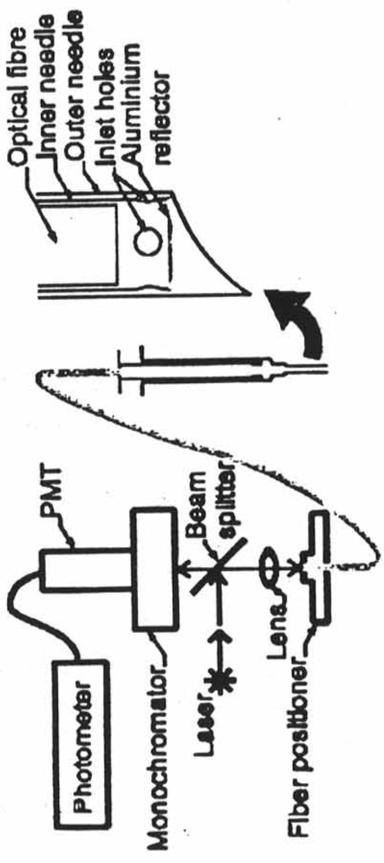
Quartz microbalance as mass sensitive transducer with Resorcin[4]-arene

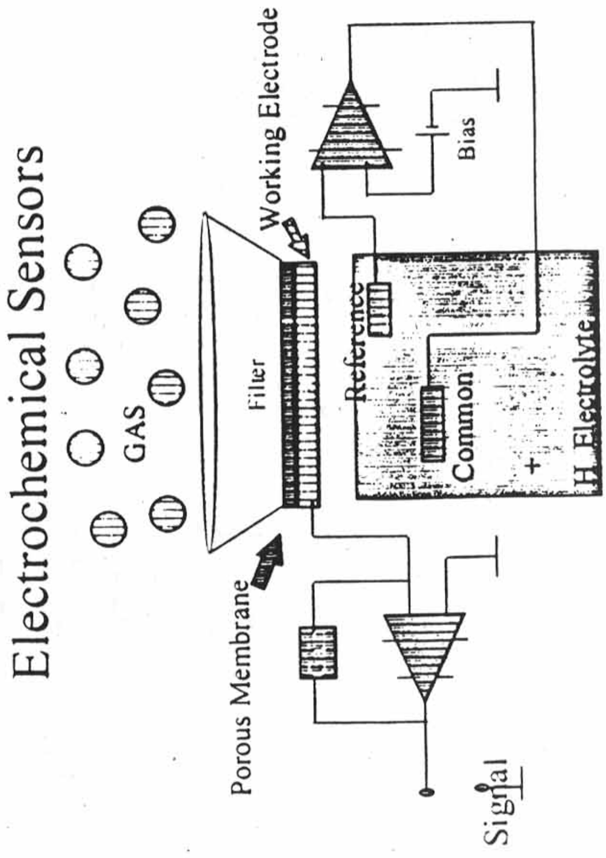
University of Tübingen
Institute of Physical and Theoretical Chemistry
Center of Interface Analysis and Sensors: W. Göpel

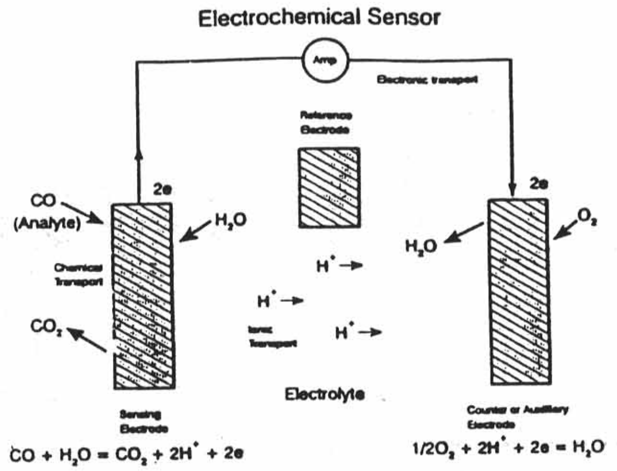
Sensor with SAW as Mass-sensitive Transducer



I:\Weimar\Bilder und Folien\Transducer\Sensor with SAW as Mass Sensitive Transducer.dsf



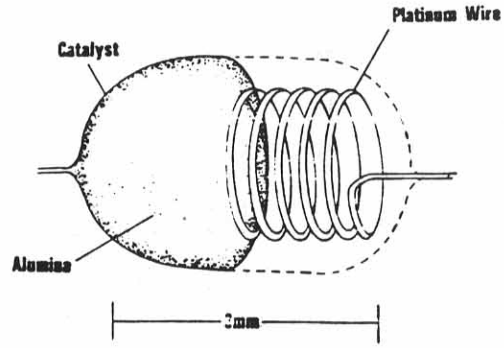




$CO + H_2O = CO_2 + 2H^+ + 2e$

$1/2O_2 + 2H^+ + 2e = H_2O$

Cell Reaction: $CO + 1/2\ O_2 = CO_2$



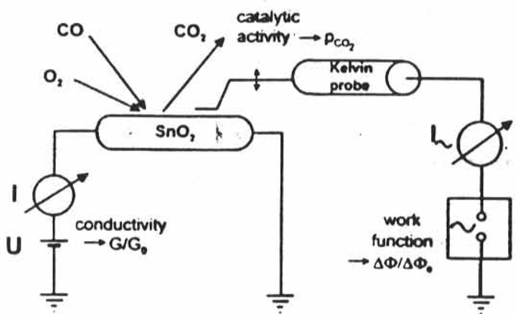
SENSOR STRUCTURE

$CH_4 + 2O_2 = CO_2 + 2H_2O + \Delta H$

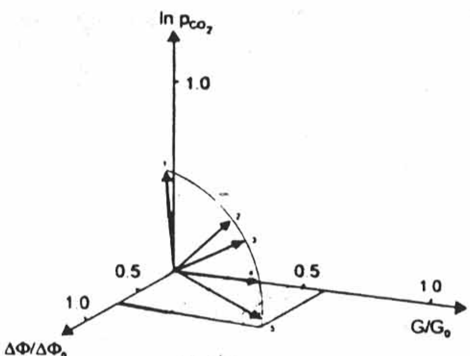
$\Delta H = C_p \Delta T$

$V_s = K[CH_4]$

a)



b)



	p_{co}/p_{H2O}
1	1 0000
2	0 0225
3	0 0074
4	0 0029
5	0 0012

CHEMICAL SENSORS are marked by DIVERSITY

- Principles of operation
- Markets and Applications
- Designs and Methods of Fabrication

INVESTMENT IN CHEMICAL SENSORS OCCURS ABROAD

- More conferences - IMCS, Eurosensors
- More publications - S&A, VCH, ...
- More federal support - TT Centers
- More new products - 7 new EN systems

PROMOTION OF CHEMICAL SENSORS as a BUSINESS is IMPORTANT to the USA

- New business in the new millenium
- Interactions that create advanced chemical sensors capable of capturing major new markets
- Repeaping the benefit of technical developments - Ens, CO, O_2, ...

THE USA HAS A SMALL SHARE OF SOME CHEMICAL SENSOR MARKETS!

- Home CO - consumer product
- Toxic and combustible gases
- Medical oxygen

Recommendations

- Promote interactions of large and small companies
- Bridge cultural gaps with flexibility - don't be rigid in technology or approach
- Take advantage of large NA Markets
- Create teams with diversity to bring the new chemical sensor products to reality

Challenge: to Overcome cultural and motivational differences.

- ***Businesses*** - shareholder value, accountable
  - ***Large*** - infrastructure, experience, finances,..
  - ***Small*** - innovative, entrepreneurial, technology rich but marketing/distribution poor,...
- ***Government*** - societal benefit, equalizer, supportive, ...
- ***Academia*** - education, knowledge, publish, creativity, unbiased, ...

Key to New SENSOR DEVELOPMENTS

- **SET CLEAR SPECIFICATIONS and GOALS**
- **ANALYZE CURRENT SENSORS AND ISOLATE AND IDENTIFY EXACT DEFICIENCIES AND REQUIREMENTS.**
- **FOCUS EFFORTS TO OVERCOME DEFICIENCIES.**
- **WORK IN PARTNERSHIP WITH INDUSTRY, GOVERNMENT AND INCLUDE Small Business AND University.**

There are only three real product advantages in the marketplace:

- ***Technical Differentiation*** - validity, spec...
- ***Service and Distribution*** - reliability, ...
- ***Customer Cost Reduction*** - product value.

What about the future? The New Millenium for chemical sensors?

- **Sensors**
  - **multidimensional**
  - **measure fundamental molecular properties, MW, e_{max}, K_{eq}, rate constant, E^0, pre-exponential factor,**
  - **use new materials in microgeometries.**
  - **use new geometries.**

- **Sensor Arrays**
  - **multi-dimensional and interpretive [μ-TAS].**
  - **E-nose becomes a subset of sensor array instruments**
  - **large instruments enter sensor regime [MS,..]**
  - **method for routine calibration invented**

Blue sky and rose-colored glasses.

In Tribute to Prof. W. Göpel,
31 Oct.1943 - 14 June, 1999.

Prof. Göpel and the ***micronose*** made at ETH, Zurich with Prof. Baltes.

- Intelligence, intensity, depth, and vision, Marked your technical call.
- Passion, grit, and oft unappreciated wit, Brought new science to all.

To Wolfgang:
My colleague and good friend.

Fuel Cells Session

A CRITICAL LOOK AT THE MATURING DEVELOPMENT AND UTILIZATION OF OPTICAL SENSOR TECHNOLOGIES

DOE Sponsored Workshop to Establish an R&D Agenda for Sensors for
Fuel Cells and CIDI/SIDI Engines
Lawrence Livermore National Laboratory

January 25-26, 2000

Jacob Y. Wong, Panelist
Ion-Optics, Inc., Waltham, MA

A PARTIAL LIST OF IMPORTANT GAS DETECTION METHODS

- ***OPTICAL***
- Non-Dispersive Infrared (NDIR)
- Laser diodes & Filter-On-Photo detectors
- Integrated Optics (IO) Interferometric Sensors
- ***ELECTROCHEMICAL***
- ***METAL OXIDE SEMICONDUCTORS (SnO_2)***
- ***THICK FILM ZIRCONIA (ZrO_2)***
- ***PELLISTORS (Catalytic Bead)***

FUEL CELLS AND CIDI/SIDI ENGINES SENSOR NEEDS

- *FUEL CELLS*
- **Carbon Monoxide I (*After shift Reactor & before PROX*)**
- **Carbon Monoxide II (*After PROX*)**
- **Tetrahydrothiophene (Sulfur)?**
- *CIDI/SIDI Engines (ODEGA)*
- **NOx**
- **Particulate Matters (PM)**
- **HC**
- **CO**
- **Ammonia (NH3)**
- **CO2**

Ion Optics, Inc.

COMPARISON AMONG THE THREE MOST IMPORTANT GAS SENSOR TECHNOLOGIES

	NDIR	Electrochemical	Thick Film Zirconia
In Line?	YES	NO	YES
Stability	YES	??	?
Interference Rejection	YES	??	YES?
Environmental Survivability	YES	??	YES
Life	Excellent	Average	Excellent?
Unit cost	$ 25-150	$10 - ?	$20 -?

Ion Optics, Inc.

A HISTORC LOOK AT NDIR GAS SENSOR TECHNOLOGY

	Pre-1990	Post-1990	Second Generation
Overall Performance	Adequate	Very Good	Excellent
Stability	Marginal	Very Good	Excellent
Interference Rejection	Adequate	Very Good	Very Good
Environmental Survivability	Marginal	Marginal	Very good
Life Expectancy	3 – 5 Years	5 –10 Years	> 10 Years
Unit Cost	$ 2 – 5 K	$ 0.15 – 1.0K	$ 25 - 150

Ion Optics, Inc.

CURRENT STATUS OF NDIR GAS SENSOR TECHNOLOGY

- Past First Generation Technology
- Overall Performance beginning to pull away from other gas sensor technologies
- Uniquely suitable for Fuel Cells and ODEGA utilization
- Very low unit cost (<$30) remains an issue but will be adequately solved with Second Generation Technology

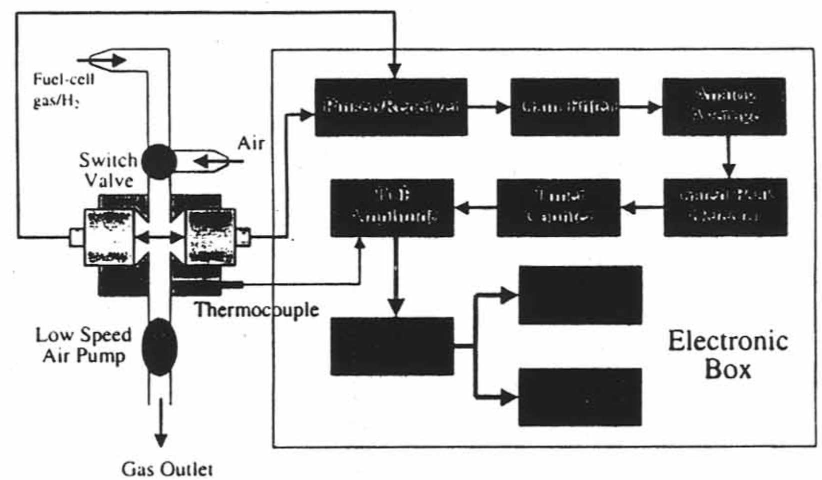
Ion Optics, Inc.

Gas Sensors for Fuel Cell Process Monitoring

Shuh-Haw Sheen, Hual-Te Chien, and
Paul A. C. Raptis

Energy Technology Division
Argonne National Laboratory

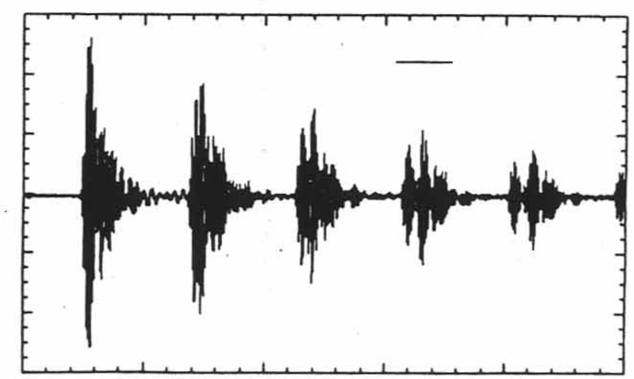
Conceptual Design of Ultrasonic Hydrogen Monitor



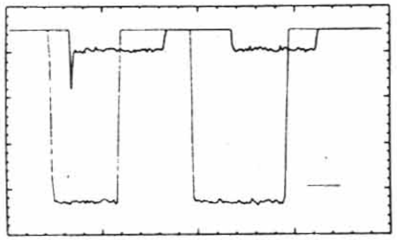
Sound Velocities of Gases

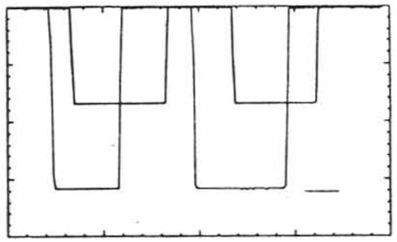
Gas	H_2	CO	CO_2	N_2	Water Vapor	H_2S
Sound Velocity m/s	1315	352	270	353	405	302
Percent Volume in Fuel Cell Gas Stream	38	50ppm	24	30	~8	1ppm
5th Echo TOF Change μsec (Relative to Dry N_2)	-45	2.5×10^{-6}	12	0	-1.7	2.7×10^{-5}

Ultrasonic Signal for Echoes of Air and 5% Hydrogen in Nitrogen



Amplitude and TOF Changes in 1% and 5% Hydrogen in Nitrogen

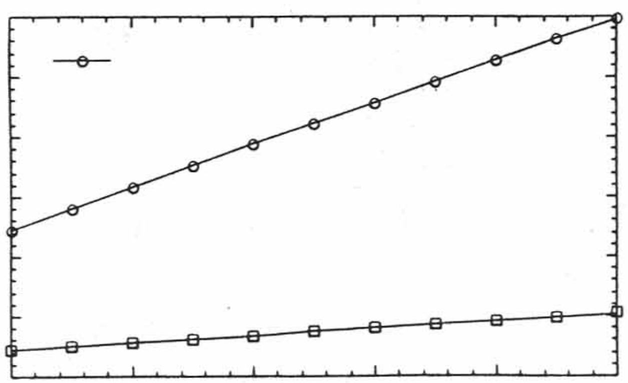




Ultrasonic Hydrogen Sensor

- Insensitive to CO and H_2S that are present in fuel-cell gas stream
- Fast response and no recovery time required
- High sensitivity (~ 100 ppm)
- Robust and resistant to chemical attack

Detection Sensitivity of TOF Measurement



Denny Wheeler

INTERNATIONAL FUEL CELLS

- Sensor Functions in Fuel Cells
  - Diagnostic
    - Early State of Development of PEM
      - Large Number of Diagnostic Sensors
  - Control
    - 90% of PEM Combined with Diagnostic (Today)
    - Established Technology: PAFC
      - Greater than 40 sensors including all design options
        - » Combined Control & Diagnostic

1

INTERNATIONAL FUEL CELLS

• Sensor Types: PEM	• Sensor Function
– Thermocouples	– Control and Diagnostic
– RTD	– Control
– Pressure	– Control and Diagnostic
– Differential Pressure	– Control and Diagnostic
– Flow (mass & volumetric)	– Control and Diagnostic
– Liquid Level	– Control
– Temperature Switches	– Control
– Level Switches	– Control
– Flow Switches	– Control
– Gas Analysis	– Diagnostic
– Conductivity	– Diagnostic

2

INTERNATIONAL FUEL CELLS

• Gas Sensors: PEM	• Sensor Function	
– Gas Analysis		
• Hydrogen	– Diagnostic	0 - 100%
• Oxygen	– Diagnostic	0 - 1005
• Carbon Monoxide	– Diagnostic	0 - 500 ppm
– Conductivity		
• Water	– Diagnostic	

3

CIDI/SIDI Session

Review: National Laboratory Sensor Projects for CIDI/SIDI Engines

DOE Workshop on Sensors for Fuel Cells and CIDI/SIDI Engines

January 25, 2000

Richard W. Cernosek
Sandia National Laboratories
Albuquerque, NM

Presentation Outline

- Vehicle exhaust gas constituent sensors being developed under DOE CRADA 94-MULT-912-ES (LANL, LLNL, ANL, and SNL with USCAR/LEP)
- Other gas sensor technology development at the National Labs
  - NOx, CO, HCs, O_2, H_2
- Other sensor developments for engine systems
  - Particulate counters
  - Pressure monitors
  - Fuel vapor sensors
  - Fluid monitors
  - Rotation/position sensors

LANL Sensor Development

Fernando Garzon- Project Leader, Eric Brosha, R. Mukundan and David Brown -Technical Staff

- Goal - develop with USCAR new ceramic sensors that measure hydrocarbons/carbon monoxide directly
- Electrochemical ceramic sensors capable of *insitu* operation (temperatures from 400-900 C)
- All new autos use ceramic zirconia sensors -proven technology
- Good sensitivity and fast response
- Simple transduction voltage or current electrical signal
- Ease of sensor fabrication and detector system implementation "spark plug" type device
- Fast light off -micro-sensors can be self-heated

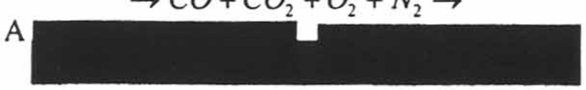
LANL Sensor Development Cont.

- A non-equilibrium potential develops at an electrode in the presence of reducing-gases
- Detect reducing-gases (H_2, CO, hydrocarbons, NO_x) in an oxygen containing stream
- Mixed Potential is fixed when the rates of the reduction and oxidation reactions are equal
- The Mixed Potential is different on dissimilar catalytic electrodes
- Potential difference between electrodes A and B is sensor response

$\frac{1}{2}O_2 + V_O + 2e \leftrightarrow O_O$ $\qquad$ $CO + O_O \leftrightarrow CO_2 + V_O + 2e$

$\rightarrow CO + CO_2 + O_2 + N_2 \rightarrow$

Electrode A

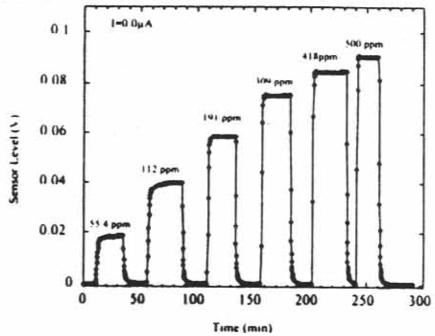


Electrode B

Solid electrolyte

LANL Sensor Development Cont.

•LANL sensors show fast reproducible responses to hydrocarbons such as propylene



•Long term stability and durability- over 3000 hours of laboratory testing under simulated exhaust gas mixtures

•Ongoing engine testing with USCAR for use as OBD II sensors

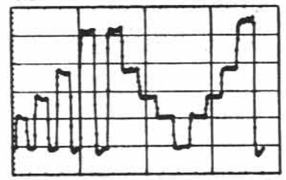
•Patent applied for sensor technology

3 electrode device mounted onto a ceramic tube with a glass seal

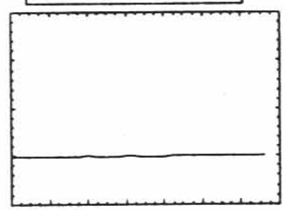
Alamos National Laboratory, Materials Science and Technology, Electronic and Electrochemical Materials and Devic

Characteristics of LLNL HC sensor

Sensor response to C_2H_6



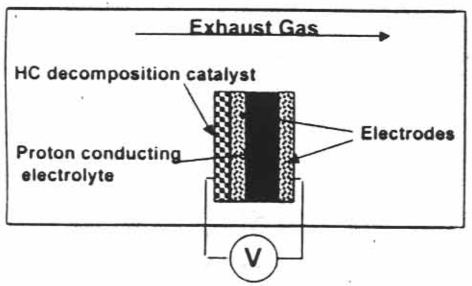
Sensor response to CO



- sensor responds to various HCs in both lean and rich conditions
- no drifting
- response time is less than 5 s
- absolute selectivity versus H_2 and CO
- no flow rate dependence
- weak temperature dependence
- some oxygen dependence

The first generation sensor has been submitted to dynamometer test at Ford Research Lab

At Lawrence Livermore National Lab, we are developing solid state electrochemical sensors for HC emissions monitoring

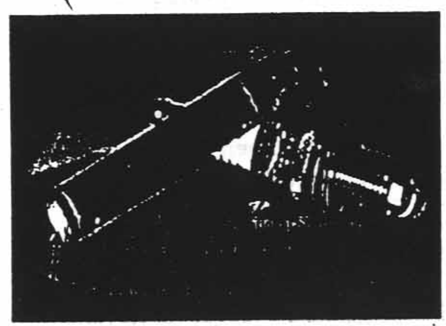


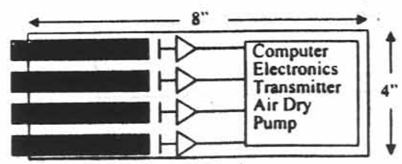
Principle of operation: this is a catalytic versus non-catalytic sensing mechanism. Various catalysts can be used to decompose HCs to hydrogen. The excess hydrogen concentration is detected by the hydrogen sensor.

Advantages:
- simple
- robust
- low cost
- can be very selective

Ai-Quoc Pham, (925)423-3394, pham2@llnl.gov
Robert S. Glass, (925)423-7140, glass3@llnl.gov

Exhaust HC Ion Mobility Sensor





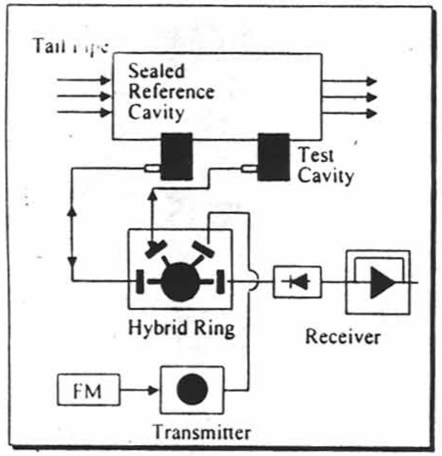
Chemical Selective Membranes

Description:
- Miniaturized intelligent ion mobility sensor array incorporates chemically selective membranes.
- Multiple chemically selective membrane inlet system provides enhanced specificity over conventional IM system.
- Capable of analyzing samples from semivolatiles, and volatiles without preparation with high sensitivities.

Applications:
- Land Mine detection
- Explosive detection
- Troop security
- Clandestine or covert operations
- Cooperative treaty monitoring
- Law enforcement support
- Chemical weapons detection
- Detection of nuclear proliferation activities/facilities

ARGONNE 50 YEARS

Microwave Sensor for Bulk Measurement of NOx

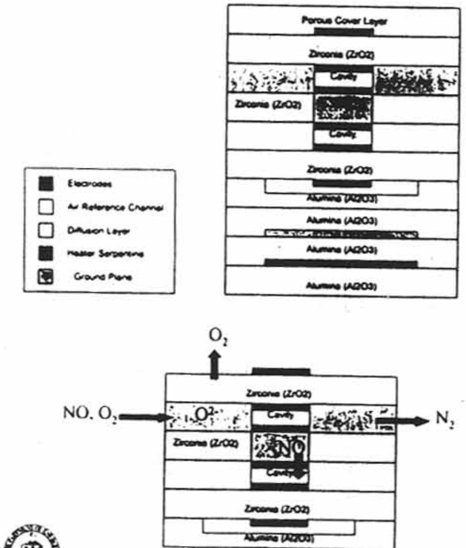


Description:

- Based on microwave rotational absorption of dipolar gases
- Uses low-cost, compact cavity or microstrip resonators to increase effective absorption path lengths
- Differential sensing with dual sensors allows robust measurements
- Frequency range is selected to maximize NOx absorption
- Immune to particulates or sulfur contamination on the sensor
- Natural discrimination to nonpolar gases like methane and CO_2

ARGONNE 50 YEARS

ORNL NOx Sensor

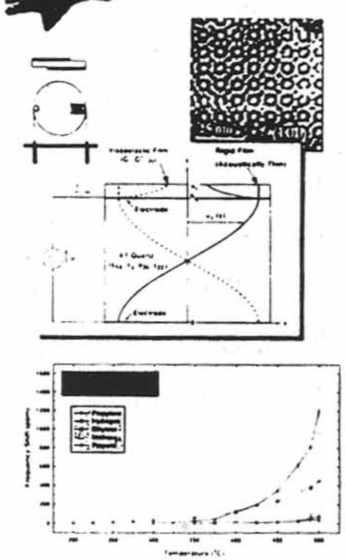


Sensor Type #1 (Gasoline lean burn engine)
Sensitivity: 100-200 ppm (potential lower detection limit for diagnostics)
Accuracy: +/- 20 ppm
Response Time: < 1 sec (0-90% full scale)
NO/NO_2: equally sensitive to NO and NO_2
Concerns: sulphur

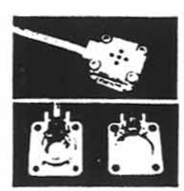
Sensor Type #2 (Diesel application with urea)
Sensitivity: 20-300 ppm
Accuracy: +/- 20ppm
Response Time: < 1sec (0-90% full scale)
NO/NO_2: separately measure NO and NO_2
Concerns: soot, sulphur and urea(NH_3)

Contact:
Tim Armstrong
Oak Ridge National Laboratory
(423) 574-7996
armstrongt@ornl.gov

SNL Acoustic Wave HC Gas Sensor



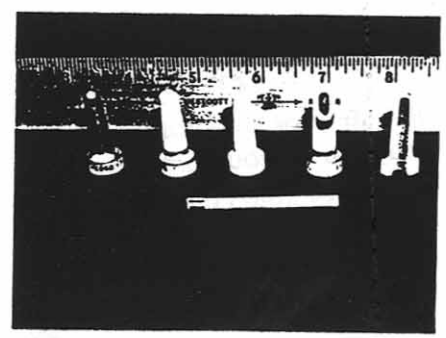
- Sensor consists of AT-cut quartz TSM resonator with catalytic-metal-doped porous silica thin film on surface.
- CTAB surfactant in sol-gel templates pores and achieves high surface area (> 700 m^2/g). Pd doping elicits strong HC response.
- Catalytic combustion of HCs + O_2 in film increases the temperature, stressing resonator surface, and shifting frequency. Response is similar to a calorimeter.
- Operation to ~ 525 °C. Quartz Curie point 573 °C.
- Min. detection limits < 50 ppm [C_3H_6]
  Response time: few seconds
  O_2 dependent response at high conc.
  No cross-sensitivity to CO or NOx
  Small sensitivity to CO_2 and H_2O
- Prototype system being prepared for performance evaluation



PI Richard W Cernosek (505)845-8818 rwcerno@sandia.gov

Sandia National Laboratories

Accomplishments in PNNL Oxygen and NOx Sensor Development Programs



Development of:

- Aqueous tape casting system
- High electrical resistance barrier layer
- Porous protective layer
- Gas diffusion layer
- Novel selective electrode materials

Five year history of materials development, testing and evaluation with OEM and suppliers

Battelle

U.S. Department of Energy
Pacific Northwest National Laboratory

PNNL Sensor Capabilities

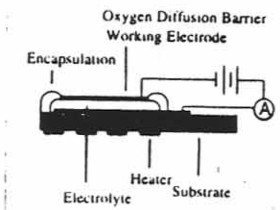
- Novel materials design and synthesis
- Materials processing (tape casting, tape calendering,…)
- Material Analysis and Characterization
  - Surface (XPS, Auger, SEM, FTIR, Raman)
  - Bulk (XRD, TEM, NMR)
- Sensor testing & evaluation
  - Gas phase (pure gases, simulated exhaust, real exhaust) using FTIR, GC/MS
  - Electrical properties

Battelle

U.S. Department of Energy
Pacific Northwest National Laboratory

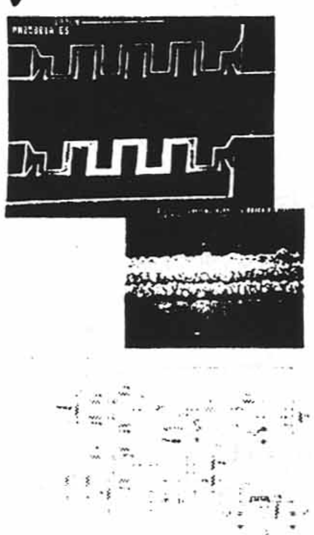
Lean-Burn Oxygen Sensors

- Zirconia oxygen sensors work well around stoichiometric (air-fuel ratio: 14.8 to 1). Potentiometric response is non-linear (λ shape) with changes in O_2 partial pressure.
- Lean-burn engines require wider dynamic range of O_2 concentrations. Air-fuel ratios > 15
- LANL and LLNL development of linear amperometric O_2 sensors with porous metal oxide or pin-hole aperture diffusion barriers.
- Linear response up to 25% O_2 partial pressure.



LANL linear response oxygen sensor

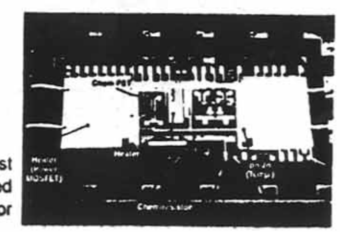
SNL Micromachined Catalytic Gas Sensor



- Suspended polysilicon filaments 2 μm thick, 10 μm wide, and 100 to 1000 μm long
- Micro-CVD deposition of catalytic Pt coating
- Combustible gases (CO, H_2, HCs) react with O_2 on filament, releasing heat
- Constant resistance (temperature) control circuit allows gas concentration to be determined from measured power
- Small suspended filaments allow for efficient electrical heating and isolation
- Dual bridge provides for self-compensating design
- Micromachining allows for batch processing and microelectronic integration
- Applications: natural gas BTU monitor, catalytic converter monitor

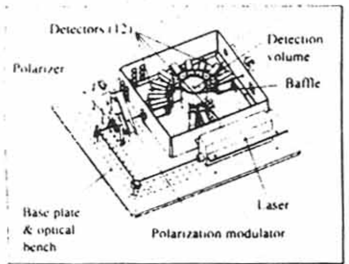
Hydrogen Detectors

- Solid-state catalytic gate (Pd-Ni) FETs [SNL]
- Thin-film Pd-Ni chemical resistor on silicon [SNL]
- Thick-film Pd chemical resistor on ceramic [ORNL]
- Optical fiber with chemochromic thin films [NREL]
- Optical fiber with Pd thin film [SNL]

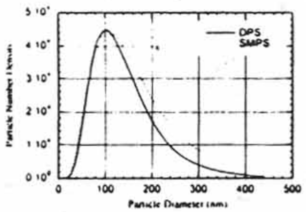


Sandia's robust integrated hydrogen sensor

Diesel Particle Scatterometer (DPS)



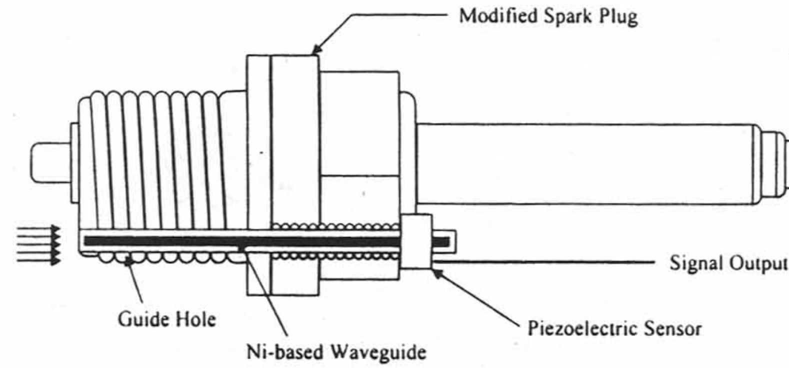
- Particulates from newer engines are smaller and more difficult to measure.
- Polarized light scattering provides rapid, accurate, and *in situ* measurement of diesel exhaust particulate characteristics:
  - size, number density, morphology, and optical properties
- DPS used to study variables: engine type, load, RPM, fuel additives, and post-combustion processes



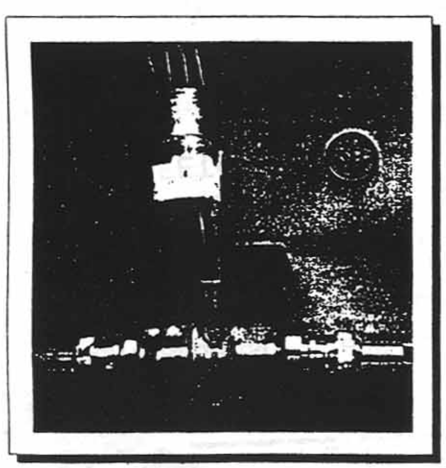
- Simultaneous measurements on Jetta Diesel engine at ORNL using the DPS, and the Scanning Mobility Particle Analyzer (SMPS) - Standard method, but slow
- Demonstrated DPS operation at > 1 Hz data rates

Arlon J. Hunt, ajhunt@lbl.gov
Env. Energy Tech. Div.

Ultrasonic Sensor for Cylinder Pressure Monitoring



Ultrasonic Particulate Monitor

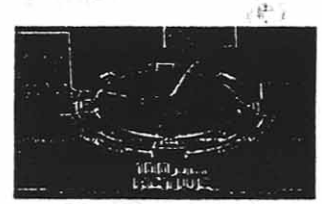


Description:
The ANL ultrasonic particulate analyzer detects particles/smoke in air by measuring changes in sound velocity and acoustic attenuation. It consists of an acoustic cavity and a pair of piezoelectric transducers operated in a pitch-catch mode.

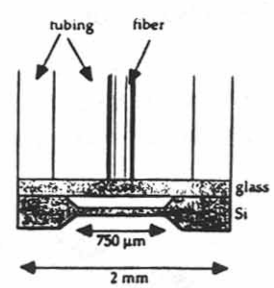
Instrument features:
- Rugged
- Low cost
- Easy operation

Other Applications:
- Helium/hydrogen leak detectors
- Radon gas detector
- Trace toxic gas detector

Pressure Sensors



- MEMS pressure sensors [SNL]
- Devices fabricated using bulk (poly-Si) or surface (SiN) micromachining
- Sensing with poly-Si piezoresistors



- Optical fiber pressure sensor using micromachined Si membrane [LLNL]
- Fabry-Perot cavity formed by glass plate and deflecting membrane
- Uses LED light source
- Dynamic range to > 1000 psi

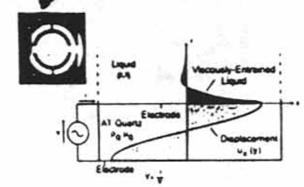
Fuel Composition Monitors

- Chemical sensor arrays detect fuel vapors.
  - Coated acoustic devices or resonant structures: SAWs, QCMs (TSM resonators), FPWs, microcantilevers [SNL, ANL, PNNL, ORNL]
  - Chemiresistors [LLNL, ORNL, PNNL, SNL]
  - ChemFETs [PNNL, SNL]
- Diverse sensor coatings are partially selective to many vapor molecules.
- Pattern recognition algorithms, neural networks, or other chemometric techniques used to identify and quantify vapors.

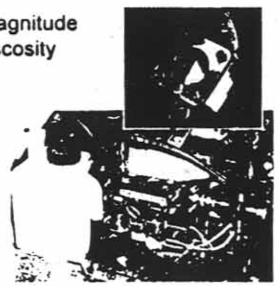
Rotation/Position Sensors

- Non-contact rotation and position sensors measure the crankshaft angle, engine rotation speed, and other shaft positions.
- Desire wide linear dynamic range, high resolution (~ 0.1%), low cost, and long life at high temperatures.
- Planar Hall effect devices [SNL]
  - InSb and InAlSb (high μ_e) on GaAs substrates
- Giant Magnetoresistance (GMR) field sensors [ORNL]
  - Alternating layers of ferromagnetic and nonmagnetic material
- Rotary differential capacitance transducers [ORNL]
  - Shaped electrodes with 25 μm polyester film dielectric

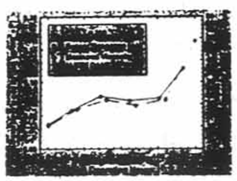
SNL Oil Viscosity Monitor



- A thickness shear mode quartz crystal resonator viscously-entrains liquid in contact with the surface
- Shifts in resonant frequency and magnitude are proportional to liquid density-viscosity



- Extracted oil samples can be placed on resonator surface
- Robustly packaged resonators can be mounted in vehicle oil pan or placed in oil flow line
- Tests conducted in laboratory, in engine dynamometers, and in operating vehicles

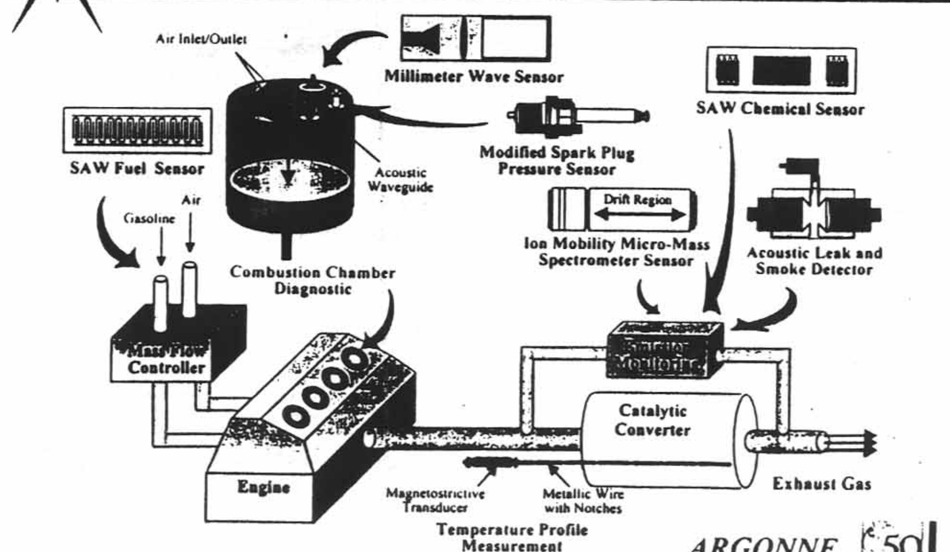


- Lubricant viscosity increases as oil degrades (oxidation due to high temperatures and pressures)
- Resonator response agrees well with viscosity measured using ASTM techniques (correlation > 0.9)

PI Richard W Cernosek (505)845-8818 rwcerno@sandia gov

Sandia National Laboratories

Total Engine and Exhaust Emission Monitoring



ARGONNE 50 YEARS

DOE SENSOR WORKSHOP

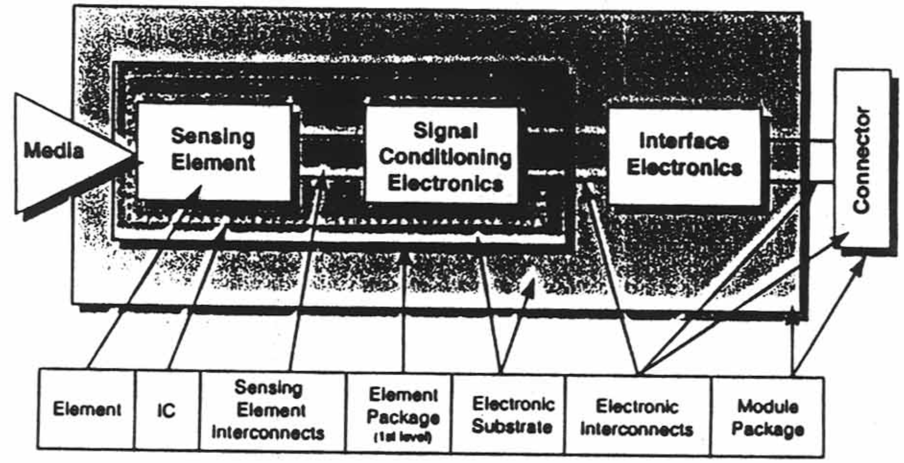
JANUARY 25 & 26 2000

JOSEPH M. GIACHINO

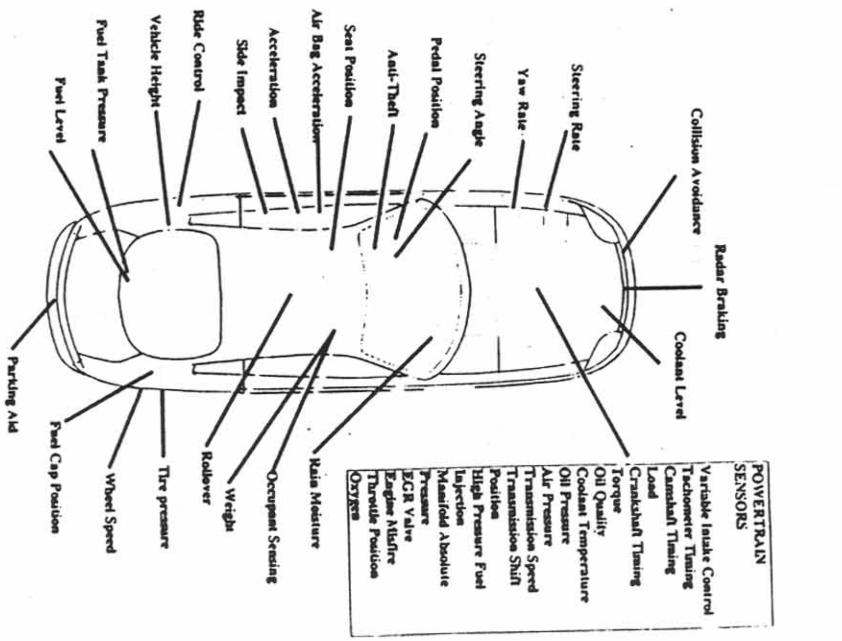
DEARBORN, MICHIGAN

Visteon

GENERIC SENSOR SYSTEM



Major Sensors for Future Vehicles



W.E. POWERS & P.R. NICASTRI "Automotive Vehicle Control Challenges In The Twenty-First Century"

SENSOR PRIORITIES

SURVIVABILITY

SELECTIVITY

SENSITIVITY

TRADE - OFF'S

ACCURACY

SPEED OF RESPONSE

ROBUSTNESS

SPAN

COST

University-based Sensor Research

Brage Golding
NSF Center for Sensor Materials
Michigan State University

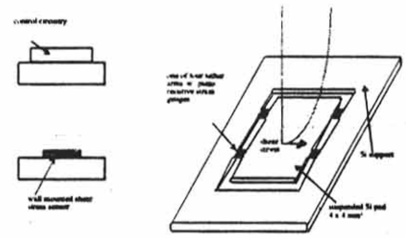
Industry	*Function*	**Powertrain** **Vehicle Control** **Safety,Comfort**	**Airflow** **Exhaust** **gas** ... ...
University	*Department*	**Chemistry** **Biology** **Physics** **EE** **MechE** **ChemE** ...	
Universities	*Research Centers*	**NSF MRSEC, STC, ERC, DOE, DOD** ...	

Sensing and Diagnostics

Emerging science and technologies

- **Air flow**
- **Hydrocarbons**
  - **semiconductor MIS**
  - **molecular imprinting**
- **Oxygen**
- **Fuel distribution**

Wall-Mounted Sensor for Flow Rates and Cumulative Flow in Unsteady Ducts



Flow rate obtained by:

- fluid shear stress on a suspended Si pad with differential strain in tether arms
- instantaneous integration of Navier-Stokes equations

Advantage of technique over conventional approaches:

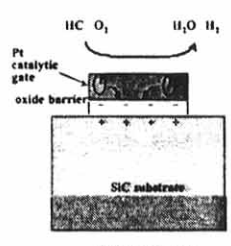
- accurate in unsteady flows
- provides flow direction

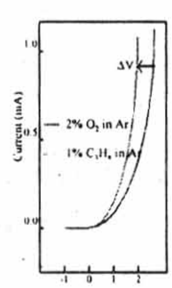
Applications:

- air intake - IC engine (mass air flow sensor)
- exhaust gas return (EGR) system

Principle of Catalytic Gate Hydrocarbon Sensor

- Efficient dehydrogenation of HC requires T>400°C
  high temperature operation => wide bandgap semiconductor





I-V characteristic of Pt-thin oxide-SiC diode @ 500°C

Schottky diode or capacitance structure:
electrical polarization => ΔV in device I-V or C-V characteristics

Brage Golding
NSF Center for Sensor Materials
Michigan State University

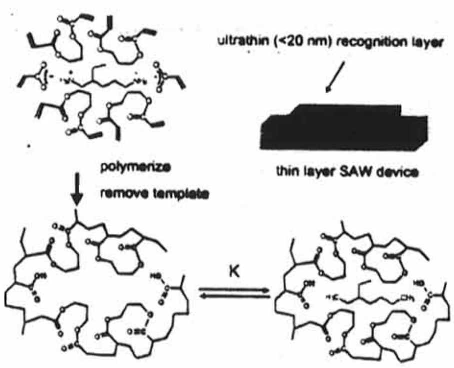
Molecular Imprinting

Enhance the specificity and sensitivity of sensing layers used in QCR and SAW devices.

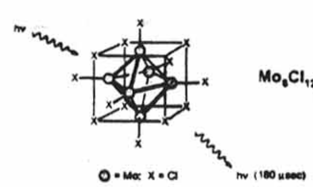
Focus on hydrocarbon analytes.

(emissions, groundwater contamination, exposure monitors)

·Thin, rigid polymer films via templating



Inorganic chromophores for oxygen sensing in extreme environments



Advantages over traditional chromophores:

Thermally stable yellow complex,
(synthesized at >600 °C from α-$MoCl_3$.)

Strong red-shifted luminescence, 100-200 μsec lifetime; quenched by $^3O_2$

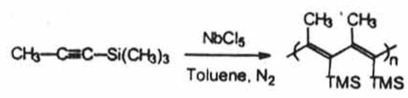
Fatigue-free chromophore (no photodegradation).

Compatible with chemically aggressive environments, i.e. acidic media to pH 1.

Brage Golding
NSF Center for Sensor Materials
Michigan State University

Polymer matrix :

- high oxygen permeability
- mechanical stability
- environmental stability
- good adhesion to fiber
- optical clarity



PTMSP

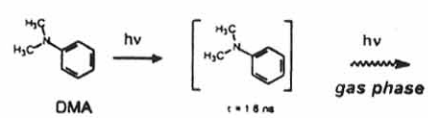
- Synthetic polymer with the highest O_2 permeability
- Oxygen selective

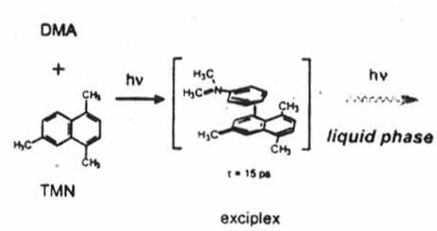
Membranes for gas and liquid separations, deep-uv photoresists, ...

Laser Induced Exciplex Fluorescence Visualization

Tag the spray with a tracer that reports independent information about liquid and vapor phases.

Space and time resolution of fuel spray.





Brage Golding
NSF Center for Sensor Materials
Michigan State University

Real-time Sensors for Intelligent Control of Automotive Engine and Processes

A. C. Paul Raptis
Energy Technology Division
Argonne National Laboratory

Tel: (630) 252-5930, Fax: (630) 252-3250, Email: raptis@anl.gov

ARGONNE

On-going Sensor Development programs for Automotive Applications

- **Tailpipe exhaust emission sensors**
  - Ion mobility time-of-flight mass spectrometer
  - Millimeter-wave spectroscopy
  - Acoustic and SAW/FPW chemical sensors
- **Leak detection and location of pressurized components**
  - Micro-mass spectrometer
  - Millimeter-wave imaging technique
  - SAW helium sensor

ARGONNE

Advanced Sensors for Automotive Engines Control

- Objectives:

  Develop advanced sensors for in-situ combustion monitoring of automotive engines.
- Scope:
  - Sensors and actuators to monitor air/fuel mixing
  - Sensors for engine performance -- In-cylinder pressure, temperature, oil film thickness and quality measurements
  - Sensors for emission control-- Emissions sensors and temperature profile sensor

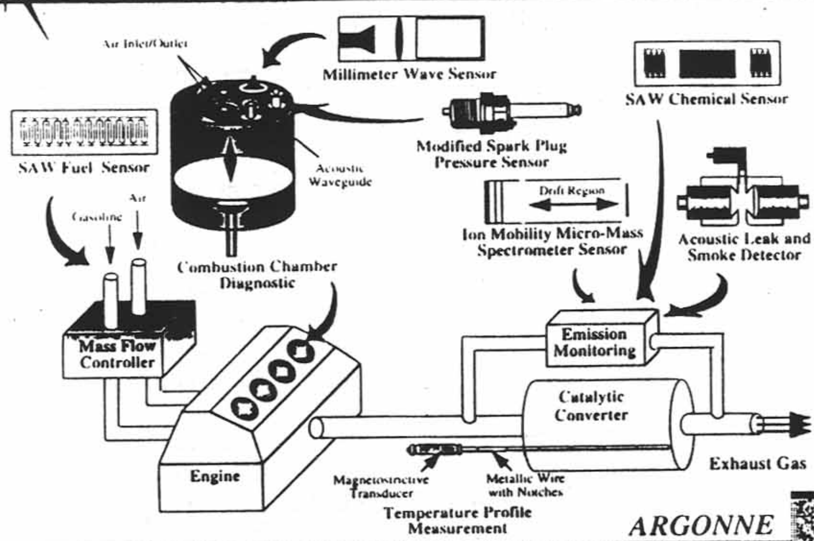
ARGONNE

Proposed Sensor Technologies

- **In-cylinder sensors**
  - Pressure sensors -- Piezoelectric and microwave cavity
  - Oil quality monitors -- Microwave and ultrasonic techniques
  - Proximity sensors -- Millimeter wave technique
- **Air/fuel Control System**
  - Air/fuel flow sensors -- SAW resonator technology
  - Intelligent valves -- Smart material technology
- **Emission Control System**
  - Chemical sensors -- Ion-mobility mass spectrometry, millimeter wave spectroscopy, and SAW micro-sensors
  - Smoke sensors -- Acoustic and microwave techniques
  - Temperature sensors for catalytic converter -- Ultrasonic methods

ARGONNE

Total Engine and Exhaust Emission Monitoring



ARGONNE

Microwave-Cavity Pressure Sensor

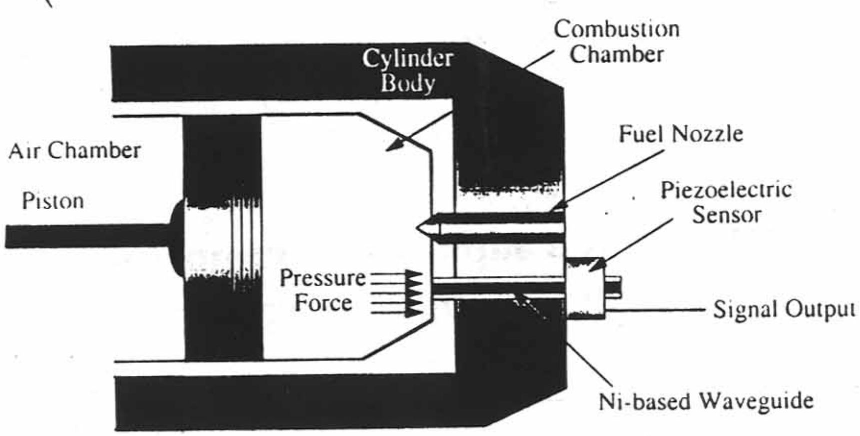
TE_{011} cavity built at Argonne

Description:
- Uses a circular cavity with a pressure-sensitive diaphragm
- The deflection of the diaphragm by pressure changes the resonance frequency of the cavity
- Multimodal excitation used to compensate for the temperature effect
- Real-time measurements

Application:
- In-cylinder pressure sensing.

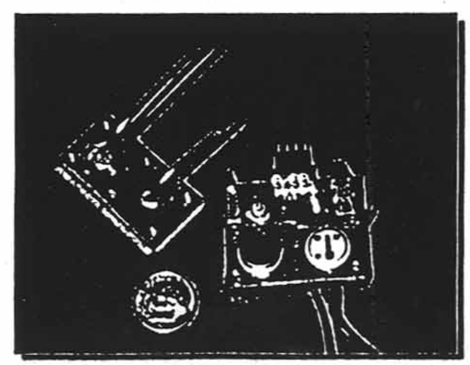
ARGONNE

Ultrasonic Sensor for Cylinder Pressure Monitoring



ARGONNE

SAW Flow Sensor



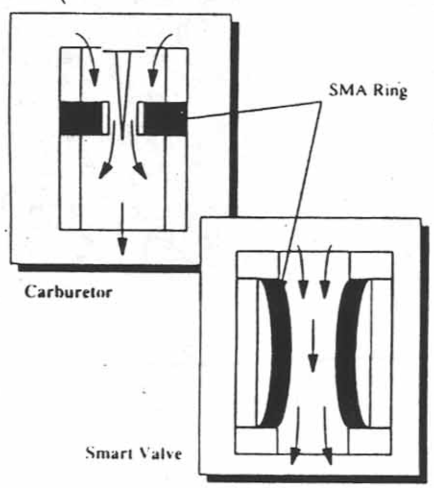
Description:
Surface acoustic wave (SAW) flow sensor based on measurement of thermal conductivity change in a gas mixture. The sensor is a 245 MHz SAW resonator on a lithium niobate substrate.

Instrument features:
- Real-time monitoring
- Easy operation
- Low cost

Applications:
- Gas flow monitoring
- Detectors for gases of different thermal properties

ARGONNE

Shape Memory Alloy Actuator and Valve



Description:
- Uses Cu-based shape memory alloy (SMA) actuators
- Adjusts SMA valve for air or fuel control and mixing
- Changes SMA orifice to compensate temperature for better air/fuel ratio
- Higher control accuracy and better reliability
- Optimizes fuel consumption and minimizes pollution

Applications:
- Automobile carburetor
- Smart valve and flow controller
- Thermostatic valve and switch
- Actuator, spring, clamp, and coupling

ARGONNE

Argonne Ultrasonic Viscometer

Non-Intrusive, Real-Time, on-Line Density and Viscosity Measurements

1994 R&D 100 Award

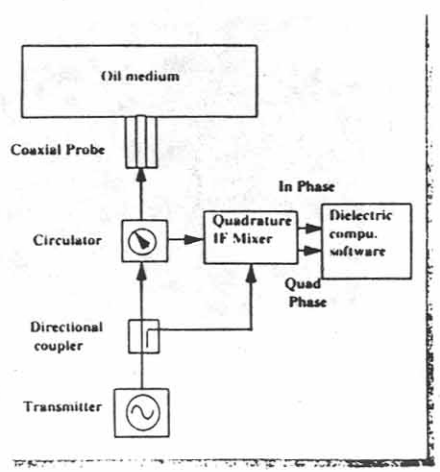
Description:
Argonne National Laboratory has developed a non-intrusive, real-time, on-line viscometer for fluid density and viscosity measurements. The viscometer is based on impedance and sound velocity measurements using both longitudinal and shear waves propagating in the fluid.

Uniqueness:
- Non-intrusive real-time monitoring
- Density and viscosity measurements
- Accurate high viscosity measurement
- Detecting homogeneity
- Rugged design
- Self-calibrating temperature/vibration effects
- Easy operation
- Low cost (< $5K)

Applications:
- Food industry
- Plastic and polymer industries
- Petroleum industry
- Laboratory bench-top instrument

ARGONNE

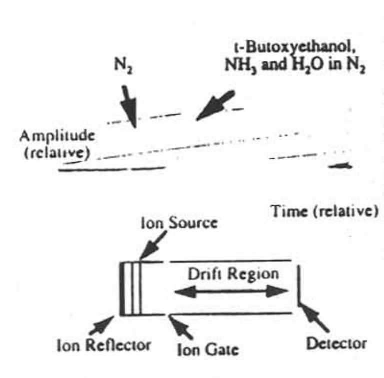
Microwave Dielectric Sensor for Engine Oil Quality Monitoring



Description:
- Based on microwave dielectric measurement
- Dielectric property changes with oil contamination
- Uses compact, robust coaxial probe
- Economical and self calibrating
- Highly sensitive to water and metal contamination

ARGONNE

Ion Mobility Real-time Exhaust Constituent Monitor

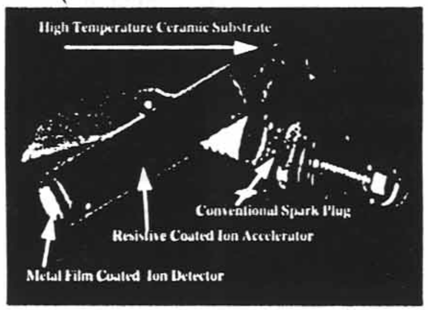


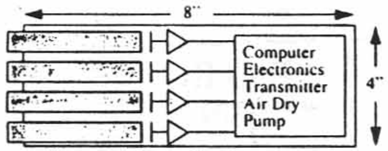
Description:
- In-car Miniaturized ion mobility spectrometers.
- Operates before or after the catalytic converter in hostile environments.
- Fast response (ms) and high sensitivity (sub ppm).
- Robust, rugged, and intelligent.
- Provides semi-quantitative analysis of total hydrocarbon constituents.

Applications:
- Emission component analysis and catalyst performance.

ARGONNE

Exhaust HC Ion Mobility Sensor





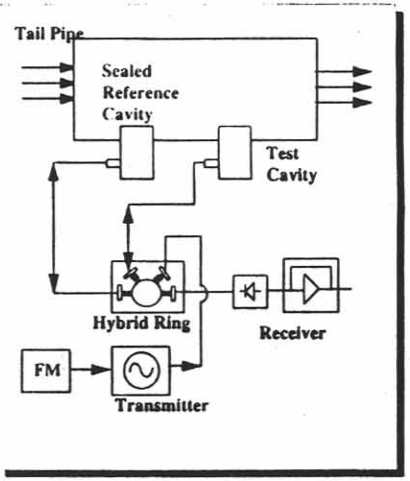
Chemical Selective Membranes

Description:
- Robust ceramic-based sensor
- Withstands extreme conditions (i.e., corrosive environments, high temperature and pressure)
- Immune to contaminates (e.g., sulfur)
- Required minimal electronics and signal processing
- PPM to sub PPM sensitivities with wide dynamic range

Applications:
- Process monitoring and control
- Exhaust emission monitoring

ARGONNE

Microwave Sensor for Bulk Measurement of Nonmethane Hydrocarbons



Description:
- Based on microwave rotational absorption of dipolar gases
- Uses low-cost, compact cavity or microstrip resonators to increase effective absorption path lengths
- Differential sensing with dual sensors allows robust measurements
- Frequency range is selected to maximize hydrocarbons absorption
- Immune to particulates or sulfur contamination on the sensor
- Natural discrimination to nonpolar gases like methane and CO_2

ARGONNE

Microwave-Cavity Emission Sensor

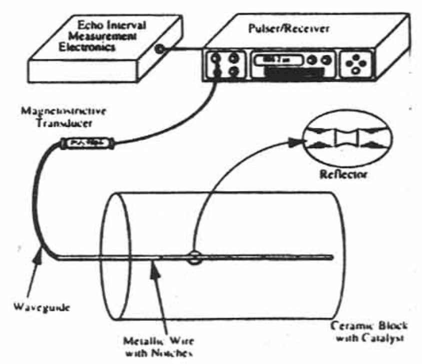

TE_{011} cavity built at Argonne

Description:
- Uses a circular cavity (2 cm radius, 6 cm height) in the TE_{011}(transverse electrical field) mode
- Tunable between 10-20 GHz
- A quality factor of ~3000 gives an equivalent path length of ~10 m
- A dual cavity arrangement in a bridge setup allows high detection sensitivity and minimizes background effects
- Stark-effect modulation can also be used to further improve sensitivity
- Real-time measurements

ARGONNE

Acoustic Temperature Sensor for Catalytic Converter

IN-SITU DIAGNOSTICS AND CONTROL OF CATALYTIC CONVERTER EFFICIENCY

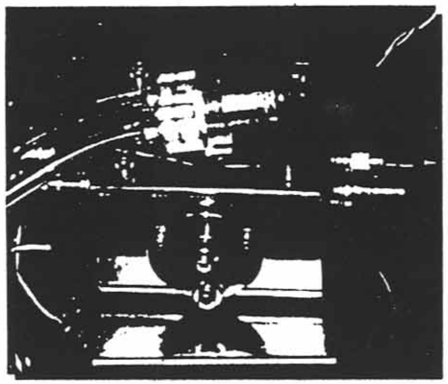


Description:
- Uses thin (fiber/wire) sensor materials without affecting gas flow
- Based on change of sound velocity with temperature
- Excellent choice of probe materials, including ceramic fibers and refractory wires
- Temperature profile measurements

Benefits:
- In-situ diagnostics and control of catalytic converter efficiency
- Temperature measurement for feedback control of engine combustion
- Reduce toxic emissions
- Life extension of catalytic converter
- Fuel flexibility

ARGONNE

Ultrasonic Particulate Monitor



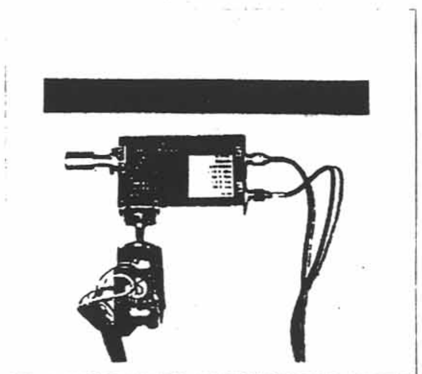
Description:
The ANL ultrasonic particulate analyzer detects particles/smoke in air by measuring changes in sound velocity and acoustic attenuation. It consists of an acoustic cavity and a pair of piezoelectric transducers operated in a pitch-catch mode.

Instrument features:
- Rugged
- Low cost
- Easy operation

Other Applications:
- Helium/hydrogen leak detectors
- Radon gas detector
- Trace toxic gas detector

ARGONNE

Millimeter Wave Proximity Sensor

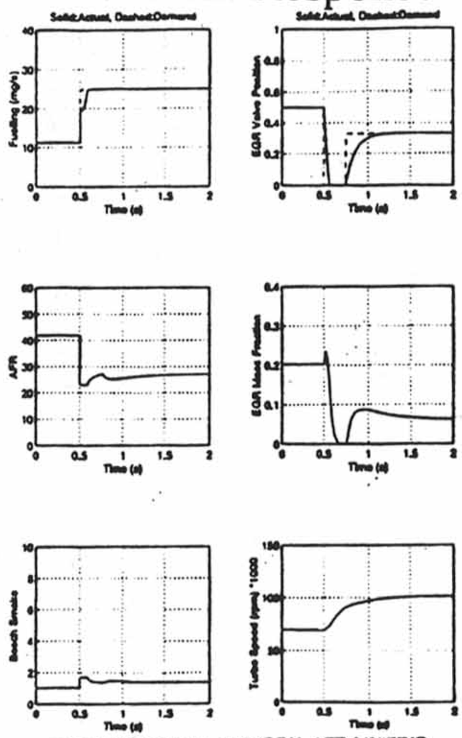


Description:
- Uses FM-CW radar technique for proximity sensing
- Compact 94-GHz mm-wave transceiver at built at Argonne
- Works under obscuring weather conditions

Applications:
- Collision avoidance system
- Object detection in earthmoving/ mining operations
- Intelligent Vehicle Highway Systems

ARGONNE

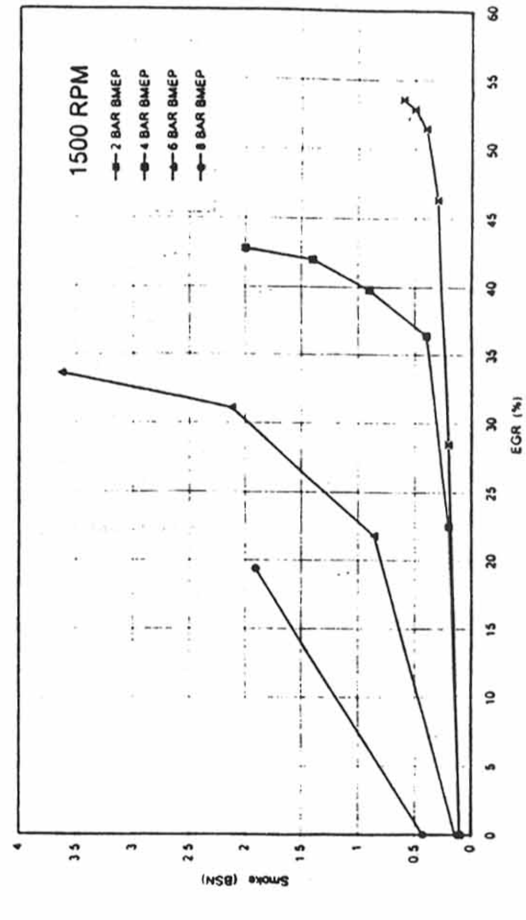
Smoke Sensor for Diesel Feedback Control - Transient Response



TRANSIENT VALVE AND IDEAL AFR LIMITING

Source: Ricardo

Smoke vs. EGR

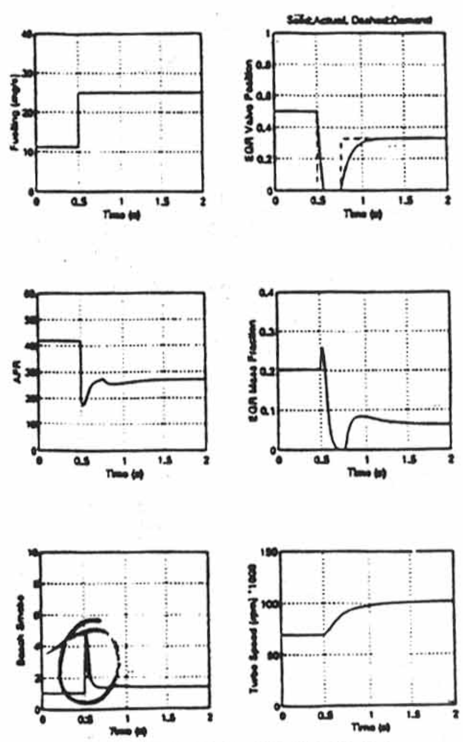


Diesel Close-Loop Control via Smoke Sensor

Frank Zhao & Tom Asmus

DaimlerChrysler

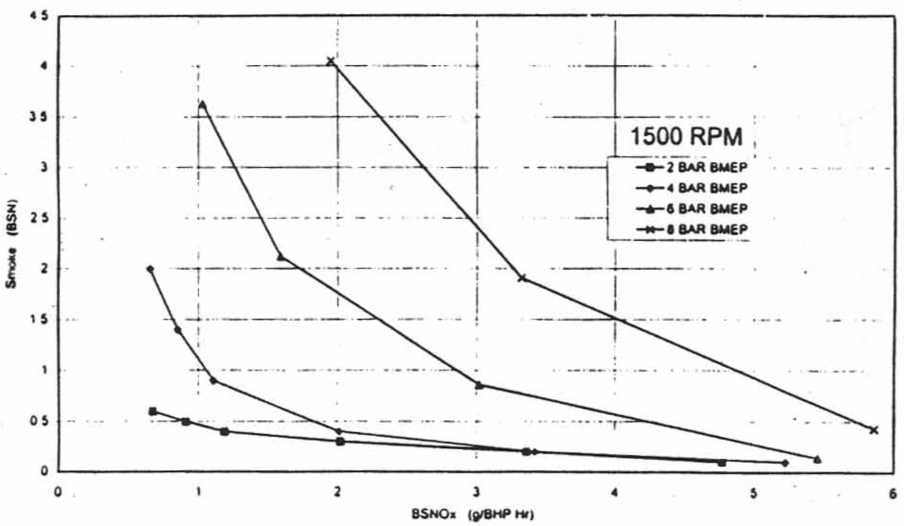
TRANSIENT CONTROL CHARACTERISTICS OF A TURBO DIESEL WITH EGR



TRANSIENT VALVE COMPENSATION

Source: Ricardo

Smoke vs. NOx



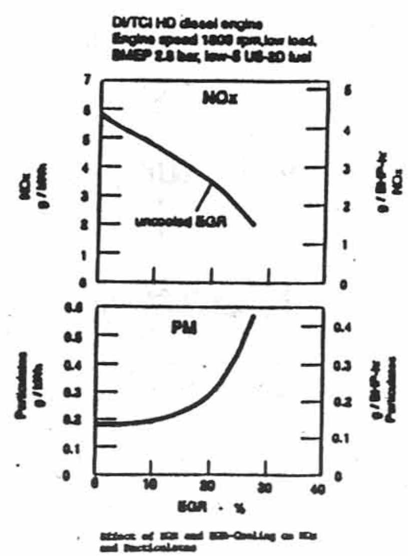
T. ASMUS

EGR FOR DIESEL NOx CONTROL

In-Cylinder Vs. Tail-Pipe Sensors

PM Sensor for Diesel Engine Feedback Control – System

- Why a PM sensor?
  - NO_X always decreases with increasing EGR rate
  - NO_X and Oxygen are correlated with PM, but still require some assumptions
  - Enough EGR to reach PM limit will always produce the lowest NO_X
  - PM is highly non-linear at the PM limit
  - Can provide compensation for both fuel and engine component tolerances



PM Sensor for Diesel Engine Feedback Control

- Assumptions
  - It has been assumed that the sensor in question will have:
    - A highly non-linear signal change near the PM-limited A/F giving a near-digital characteristic.
    - Output signal proportional to the smoke level continuous from 0 to > 5 BSU
    - Output signal will be independent of sensor temperature or other exhaust gas components
    - As an OBD device, the sensor will have > 150,000 mile durability

PM Sensor for Diesel Engine Feedback Control - Applications

- Maximize EGR rate under all speed/load conditions subject to a PM-level constraint.
  - Minimize open-loop dynamometer calibration effort
  - Compensate for wear or drift in injectors, air management system...over time

PM Sensor for Diesel Engines Feedback Control - Applications

- Given a sufficiently fast response sensor, one could identify cylinder-to-cylinder smoke variations and compensate the fueling rate accordingly.
  - Minimize impact of part-to-part variation
  - Injector diagnostic
  - Swirl port deactivation diagnostic

PM Sensor for Diesel Engines Feedback Control - Applications

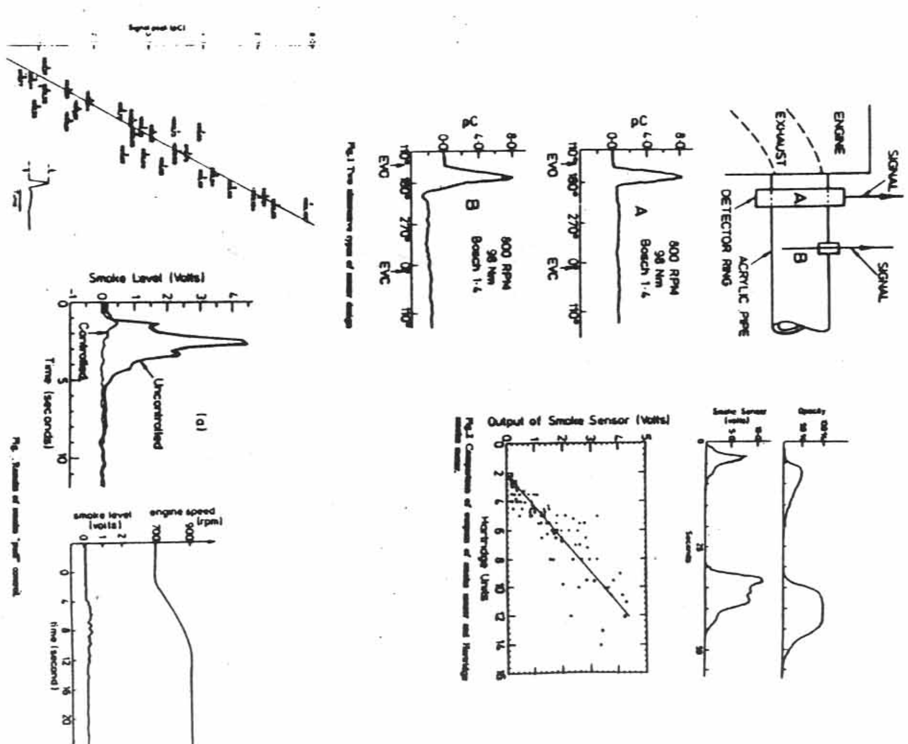
- Full load fuel control
  - Control full load fuel control via PM level feedback rather than a pre-set fuel quantity based on worst-case conditions
  - Compensate for injector wear-drift over time
  - Altitude compensation
  - Minimization of effect of part-to-part variation on setting full load conditions

PM Sensor for Diesel Engines Feedback Control - Applications

- EGR function diagnostic – OBD
  - At a set condition, should be able to detect a difference in PM level with and without EGR and possibly diagnose EGR function
- VGT / Wastegate function diagnostic
  - Similar to the above, at set condition, varying the boost pressure should make an impact on PM levels.

Smoke Sensor for Diesel Feedback Control - Applications

- Pilot Injection function diagnostic
  - At a set condition, should be able to detect a difference in smoke level with and without pilot injection.
- Transient sensor response could be used for tuning manifold filling models.
- Allow the engine to compensate for fuel property changes.



Richard Soltis

Ford Motor Company

NO_x Sensors

- Uses: NO_x sensors are needed for
  - Feedback control
  - Monitoring (OBD)
- Applications
  - Diesels
  - Lean Burn
  - Stoichiometric Control

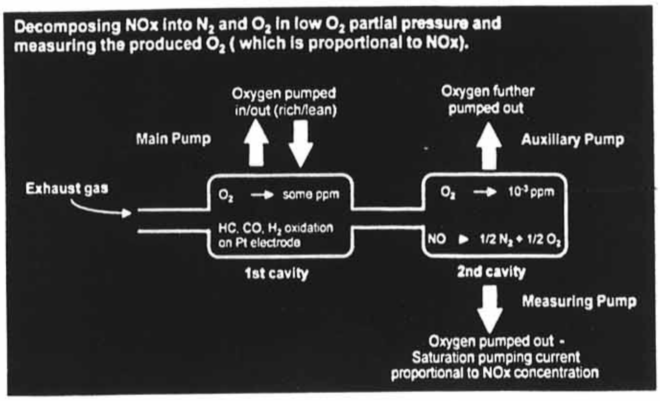
NO_x Sensors: Diesel Applications

- HC injection NOx diesel treatment
  - near-term – light trucks
- Urea-based NO_x diesel treatment
  - long term – SUV's
- Feedback Control
  - Sensors required:
    - ⇨ NO_x
    - ⇨ Ammonia
    - ⇨ HC/UEGO ??
- Diagnostics
  - OBD required for diesels
  - HC/lean NO_x catalysts

NO_x Sensors: Lean burn Applications

- UEGO & Lean NO_x Trap (LNT) monitor
- Control
  - LNT regeneration
  - LNT de-sulfurization
  - Sensors required:
    - ⇨ NO_x
    - ⇨ sulfur
- Diagnostics
  - LNT monitor using HEGO to measure O_2 storage capacity of trap
  - Indirect measurement
    - ⇨ Need NO_x sensor

Zirconia-based NO_x Sensor

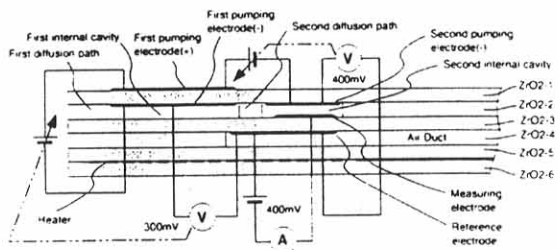


Can simultaneously function as O_2 sensor

NO_x Sensor

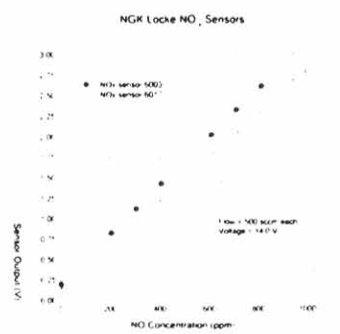
- NO, NO_2 thermodynamically unstable
- large activation energy to dissociate
- interfering gas (O_2) removed in first cell
- NO_x decomposed in second cell
- liberated oxygen pumped out by second cell
- saturation pumping current proportional to NO_x concentration
- appropriate electrode catalyst selection
  - ñ 1[st] cell non-catalytic
  - ñ 2[nd] cell catalyzes decomposition of NO_x
- ideally NO_2 gives twice signal of NO for same concentration

Planar Schematic (NGK Locke)



- 3 cell design with diffusion barriers
- air reference
- 1[st] cell reduces O_2 pressure to constant level
  - ñ tens of ppm
  - ñ NO does not dissociate
  - ñ NO_2 dissociates ∅ NO + ΩO_2
- 2[nd] cell uses Rh electrodes
  - ñ effective to dissociate NO
- Use non-catalytic Au/Pt electrodes

Calibration Curves - NO



- Concentrations up to 1000 ppm
- Some sensor-to-sensor variability
- after 5 min. warm up, no drift in zero for up to 72 hours continuous operation

Issues

- Durability
  - Drift
  - Ageing effects
- Sensitivity
  - 10 ppm NO
  - Small signal (~ 10nA/ppm)
    - ⇨ Packaging
    - ⇨ Electronics
- Selectivity
  - NO vs. NO_2
  - Ammonia & HC interference
- Poisoning
  - Soot, sulfur
- Response time (500 msec.)
  - Monitoring vs. control
- $$$COST$$$
  - Complicated structure
  - Electronics
  - Calibration